11-6-2015

Environmental Life Cycle Comparison of Aluminum-based High Barrier Flexible Packaging Laminates

Jacob A. Bayus
jb8888@rit.edu

Environmental Life Cycle Comparison of Aluminum-based High Barrier Flexible Packaging Laminates

by

Jacob A. Bayus

A thesis submitted in partial fulfillment of

the requirements for the degree of

Master of Science in Sustainable Engineering

Department of Industrial and Systems Engineering

Kate Gleason College of Engineering

November 6, 2015

Committee Members

Brian Thorn, Ph.D.

Advisor

Associate Professor

Industrial and Systems Engineering Department

Kate Gleason College of Engineering

Rochester Institute of Technology

Changfeng Ge, Ph.D.

Professor

Packaging Science Department

College of Applied Science and Technology

Rochester Institute of Technology

Marcos Esterman, Ph.D.

Associate Professor

Industrial and Systems Engineering Department

Kate Gleason College of Engineering

Rochester Institute of Technology

Department of Industrial and Systems Engineering

Kate Gleason College of Engineering

Rochester Institute of Technology

Rochester, NY 14623

Certificate of Approval

The thesis by Jacob A. Bayus has been examined and approved by the thesis committee as satisfactory for the thesis requirements for the Master of Science degree in Sustainable Engineering.

Approved by:

Brian Thorn, Ph.D.

Changfeng Ge, Ph.D.

Marcos Esterman, Ph.D.

Acknowledgements

I would like to extend a sincere thank you to everyone who has helped me throughout this process.

Thank you to Dr. Brian Thorn for guiding me through my research process, environmental analysis methodologies, and document formatting. It has been a great learning experience.

Thank you to Dr. Changfeng Ge for allowing me to work on this project with you, and for your guidance on flexible packaging technologies. I appreciate it.

Thank you to Dr. Marcos Esterman for your support, guidance, and assistance in looking at everything from a systems perspective.

I would also like to thank my family for their constant support and encouragement, and my RIT friends for being there for me along the way.

Abstract

A common flexible packaging laminate is comprised of five constructs in sequence: printing layer, adhesive, barrier layer, adhesive, and sealing layer. Aluminum foil and metallized polymer films are commonly used gas barrier layers in flexible packaging, but their true environmental impacts are not well-represented. This study investigated the potential environmental impacts of three widely-used, five layer laminates, namely polyethylene terephthalate/aluminum foil/linear low density polyethylene, polyethylene terephthalate/metallized polypropylene/linear low density polyethylene, and polyethylene terephthalate/metallized polyethylene terephthalate/linear low density polyethylene in which the barrier layers are aluminum foil, metallized oriented polypropylene, and metallized polyethylene terephthalate. This study, with the use of SimaPro 8, was conducted to assess the total environmental impact, global warming potential, and embodied energy of these packaging alternatives across the life cycle. Compared to the aluminum foil laminate, the metallized polymer laminates offer reduced environmental impacts, though not as substantial as often cited. The results show that the MOPP laminate offers a 43% lower total impact and the MPET laminate offers a 40% lower total impact. Global warming potential is reduced by around 50% for both metallized polymer laminates, and a non-renewable embodied energy is 25-26% lower compared to the aluminum foil laminate.

Table of Contents

List of Figures

List of Tables

1. Introduction

Packaging material of all varieties is consumed rapidly all over the globe. This has led to environmental strain seen as pollution, resource reduction, landfill occupancy, etc. One common technique to combat the environmental impacts associated with packaging materials is lightweighting. This is the process of reducing the weight of a package without compromising its ability to meet specified performance measures. In most cases this technique is beneficial in that it reduces the quantity of raw materials consumed, energy consumed in transportation, and material ending up in landfills at end of life. As with any decision, especially those related to the environmental impact of a product, there are trade-offs that must be analyzed. Reducing impacts at one stage of a product life cycle will not necessarily have positive effects through the entire life cycle.

This trade off scenario is analyzed for the case of multi-layer flexible packaging commonly used for snack foods such as potato chips. Multi-layer laminated films with a metallized polymer as the barrier layer uses significantly less aluminum than laminates that use aluminum foil as the barrier layer. One trade off of this is that metallized polymer based laminates use more polymer material to provide the same service as an aluminum foil-based laminate. This research assesses the environmental performance of three aluminum-based, multi-layer flexible packaging laminates (PET/AluFoil/LLDPE, PET/MOPP/LLDPE, and PET/MPET/LLDPE) to provide insight on which is least impactful over its life cycle. Environmental impacts of each alternative are expressed as total impact (ecopoints), global warming potential (kg CO_2 eq.), and embodied energy (kWh).

2. Background

2.1. Aluminum Use in Packaging

Aluminum is the third most abundant element in the earth's crust following oxygen and silicon. It is the most abundant metallic element in the Earth's crust (Frank et al., 2009). When exposed to air, aluminum forms an oxide layer which acts as a barrier against further oxidation. This property, and the fact that aluminum is non-absorbent, allows it to inhibit the transmission of gasses and liquids (Emblem & Emblem, 2012). It is stable over a wide range of temperatures, does not generate toxic releases when exposed to most chemicals including foods, provides a barrier against gasses, liquids, and light, and can be easily formed as a foil (Emblem & Emblem, 2012). All of these properties are why aluminum is widely used in the packaging industry.

Aluminum and aluminum foil have been used in the packaging industry for many years due to intrinsic properties. As technology advances and regulations in the packaging world change, an increase in the use of flexible packaging is predicted. Flexible packaging is defined as packaging with a pliable shape such as bags, envelopes, pouches, sachets, and wraps made from easily yielding material like films, foil, or paper (Katz, 2013). It is estimated that the global flexible packaging market will grow at a rate of 3.5% per year up to the year 2018 (Smithers Pira, 2013). This means that the industry could reach 231 billion dollars by that time (Figure 1). The reason for this is that flexible packaging is much thinner than other forms of packaging; therefore, it uses less material for the same volume of product being packaged and results in less waste. This is important because aluminum is widely used in flexible packaging as a barrier layer, and in fact it comprises over 30% of the global barrier

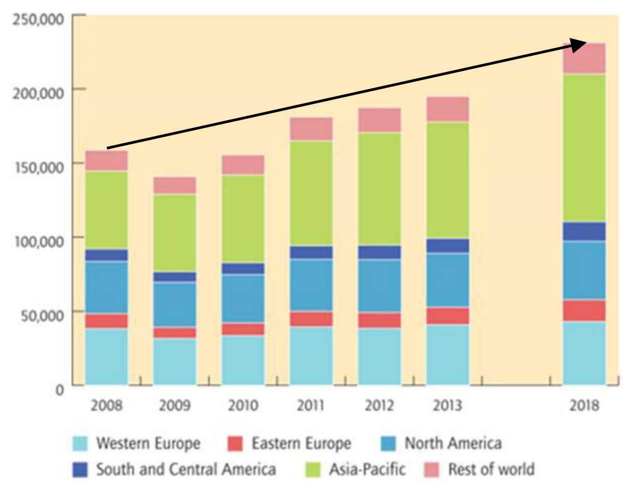


Figure 1 World forecast of flexible packaging consumption by region 2008-2018 ($ million) Adapted from Smithers Pira (2013)

packaging market (Decker, Roy, Voght, Roy, & Dabbert, 2004). As the consumption of flexible packaging increases, so too could that of aluminum.

Standard polymers used for flexible food packaging do not generally meet requirements for gas, light, and water vapor transmission (Copeland & Astbury, 2010). The transmission of gasses, or oxygen in most cases, is referred to as Oxygen Transmission Rate (OTR) and the Water Vapor Transmission Rate is referred to as WVTR. As a reference, typical demands for snack food packaging are an OTR of 5-10 $cm^3/m^2/day$ and a WVTR of 0.3-0.5 $g/m^2/day$ (Fowle, 2005). When polymers are laminated with aluminum foil to form a multi-layer package, which combines two or more layers into a composite material, the barrier properties are significantly improved and are able to reach and exceed these criteria (Emblem & Emblem, 2012; Mueller, Schoenweitz, & Langowski, 2011).

At a thickness greater or equal to 17μm, aluminum foil is a near perfect barrier to oxygen and moisture (Emblem & Emblem, 2012; SMPC, 2009). As a reference, the foil layer in most laminates is around 7 μm to 9 μm in thickness, so pin-holing is common. Foil also allows very minimal transmission of light (Decker et al., 2004). Even with small pinholes, aluminum foil is an excellent barrier and is why it was the first high barrier material for flexible food packaging. Although aluminum foil seems like the perfect barrier material to prevent food spoilage in packaging, there are downfalls. Aluminum foil used in flexible, multi-layer packaging has low crease resistance which can lead to cracks and pinholes (loss of barrier properties), it is difficult to recycle when in laminate form, it is susceptible to tearing at thinner gauges, and material use is high compared to other barrier layer options (Decker et al., 2004). These drawbacks have led to replacing aluminum foil with metallized polymers as the barrier layer in multi-layer flexible packaging laminates (Petrie, 2006).

2.2. Metallized Polymer Films

Metallization of a polymer is the process of vaporizing a metal, aluminum for packaging, in a vacuum chamber and depositing it as a thin layer (50 nm thick) on a polymer sheet (Figure 2). Aluminum wire is fed onto resistance-heated evaporation boats where it is evaporated. The polymer web, which is supported by a chilled drum, translates above the vapor field so that the vapor can condense and create the thin aluminum coating. There are four main steps for one metallization cycle which include stand-by, pump-down, metallizing, and defrost. Stand-by includes cleaning the machine and prepping the roll of polymer film; pump-down is the process of drawing the appropriate vacuum; metallizing includes the processes described above to deposit the aluminum onto the polymer material; and defrost is where the machine internals are brought up to a temperature above the dew point prior to opening (Bishop, 2015; Bobst Manchester Ltd, 2015).

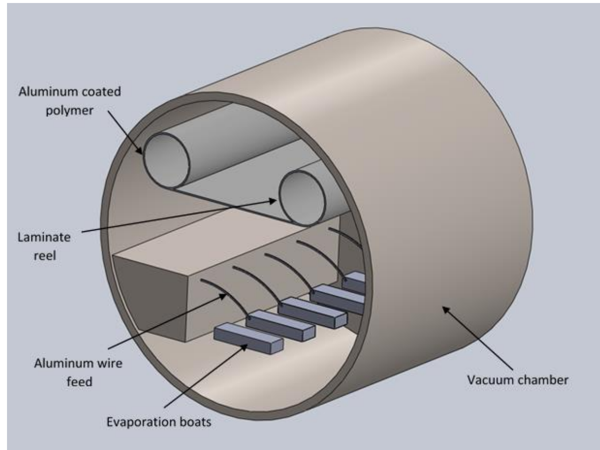


Figure 2 Vacuum metallizing
Adapted from Emblem & Emblem (2012)

The process of metallization is widely used with paper as well, but the focus of this study is that of metallized polymers. The primary reason for using metallized polymers instead of aluminum foil is that significantly less aluminum is used which translates to cost savings, material savings, and environmental benefits due to this lightweighting; thinner layers with similar barrier properties is the intention (Barlow & Morgan, 2013; Bishop, 2007; Chatterjee, 2006; Copeland & Astbury, 2010; Petrie, 2006).

Films laminated with aluminum foil are not easily recyclable; therefore, landfilling and incineration are more common end of life options (Franklin Associates, 2014). Metallized polymers significantly reduce waste and loss of embodied energy of aluminum compared to foil when disposed of in this manner. It has been claimed that when vaporized aluminum is "…applied onto a single web of film, paper, or board, the metallized substrate can be considered effectively as a monolayer structure and recycling poses no problems" (Copeland & Astbury, 2010). This refers to recycling the polymer material, and is due to the fact that the layer of vaporized aluminum deposited is on the scale of tens of nanometers in thickness. Although this may be the case, when metallized films are laminated with other polymers to form a working flexible package, their recyclability drops off due to the combined nature of the package and contamination from food residue (Barlow & Morgan, 2013; Siracusa, Ingrao, Lo Giudice, Mbohwa, & Dalla Rosa, 2014).

Using metallized polymer film as a barrier layer in multi-layer flexible food packaging is more advantageous than aluminum foil (Bishop, 2007; Chatterjee, 2006; Copeland & Astbury, 2010; Petrie, 2006). In all cases, metallized films are said to save on costs associated with processing and materials as well as with energy. Decker et al. (2004) suggests that there are three major requirements that must be fulfilled in order to replace foil with metallized film: function, economics, and feasibility. This implies that the metallized film must provide the properties delivered by aluminum foil in an economical manner, and the film must be able to run on the same equipment as foil in manufacturing. Although Decker et al. (2004) does state that environmental considerations should be made, the report mainly points to the reduction in aluminum use as the largest benefit.

Research to date has focused on the energy and material reduction, but does not address a full environmental impact analysis of these materials. No publicly released research has looked in depth at the environmental impacts of metallization processing steps, disposal, and the use phase associated with this packaging in addition to material consumption. Due to differences in scope, these reports present an underestimate in the environmental consequences associated with metallized polymers when used in a multi-layer laminate. The aim of this study is to quantify the life cycle environmental impacts associated with the use of aluminum foil and metallized films as barrier layers in multi-layer packages in order to generate a more fair comparison. Specifically, this study will compare three alternative scenarios for multi-layer bags like those used for snack foods such as potato chips.

3. Review of Literature

3.1. Energy and Material Use

One argument, in addition to material reduction, against foil use is that the process of making aluminum is very energy intensive. Aluminum is produced via an electrolysis process that requires a significant amount of electricity. It is estimated that it takes 4 kg of bauxite (material aluminum is originally derived from) to produce just 1 kg of pure aluminum (Emblem & Emblem, 2012). This whole process consumes up to 15 kWh of electrical energy ("Aluminum," 2014; Emblem & Emblem, 2012). The amount of aluminum used for metallized film as opposed to typical foil can be as much as 99% less and therefore requires significantly less energy to produce (Copeland & Astbury, 2010; Petrie, 2006).

Copeland and Astbury (2010) point to aluminum preservation and energy requirement reduction as the advantages of vaporized aluminum over foil. According to their report, the aluminum consumed for a metallized polymer compared to foil can see a "resource preservation ratio of 1:125." It also claims that the energy used to produce this layer of 50 nm vaporized aluminum, including the energy to produce the aluminum itself, is 97% less than a standard foil layer (Copeland & Astbury, 2010). These numbers point toward the efficiency in resource usage and processing energy consumption. There are, however, more conditions to consider when fairly evaluating the environmental benefits of metallized films over foil. At the very least, energy requirements for producing the polymer web onto which the vaporized aluminum is deposited, forming of the aluminum wire used as the feedstock for metallization, consumption of evaporation boats, etc. need to be considered to get a more accurate energy and environmental comparison (Bishop, 2007).

As stated, when comparing a metallized film to aluminum foil, one thing to consider for the metallized film is the necessity of, and production steps associated with, the polymer web (Bishop, 2007). Aluminum foil provides a large majority of the barrier properties associated with a laminated multi-layer package ("Aluminum Foil," 1997). Vaporized aluminum however cannot stand alone as a barrier layer and requires deposition onto a polymer web, or film. The polymer web, most often PET or OPP in the metallized barrier film industry for food packaging (Bishop &

Mount III, 2010; Copeland & Astbury, 2010), provides the structure for the film. Claims for metallized polymer films reference the significant reduction in aluminum usage in the barrier layer, but do not well-represent that the vaporized aluminum is applied to a polymer surface to act effectively as a barrier. With that being said, in order to better compare the alternatives, the materials and extrusion of the polymer web onto which the vaporized aluminum is deposited must be accounted for when comparing barrier layers.

Bishop (2007), on the topic of vacuum deposition of aluminum, clearly states this concept of looking at the whole picture when trying to accurately report the energy footprint associated with metallized films and foil. According to Bishop, vacuum metallizers consume a large amount of electricity to vaporize aluminum. The heat energy associated with this electricity is split three ways within a resistance heated metallizer. One third of this heat evaporates the aluminum while the other two thirds do not. On top of this, only half of the aluminum that is fed into the machine during the metallization process is deposited onto the polymer web due to the nature of the process (Bishop, 2007). The other half misses the web and falls onto the inner machine surfaces. When these properties, as well as the energy consumption to produce the polymer web are taken into consideration, the energy savings of metallized films compared to foil are much less than often cited (Bishop, 2007).

All of the reports discussed thus far have a common theme; they tend to focus on the material reduction and energy savings associated with vaporized aluminum compared to foil. There are, however, other metrics that can be considered in order to more fully represent the environmental impacts associated with these barrier layer options. Some impact categories to consider include climate change, metal depletion, and fossil fuel depletion to name a few. This study focuses on and quantifies environmental impact categories such as these. It also shows that the life cycle energy and carbon footprint impacts associated with metallized polymers, when used as the barrier layer in multi-layer laminates, are less than the foil laminate, but not significantly less in some aspects.

3.2. LCI Considerations

In order to compare the environmental impacts of these packaging laminates, life cycle inventory data must first be collected. This data is essentially the inputs and outputs associated with a certain aspect of the life cycle. For instance, a life cycle inventory of the process of creating metallized oriented polypropylene (MOPP) was presented by Luhrs, M., Griffing, E., Realff, M., & Overcash, M (2010). This proceeding included process electricity for heating and evaporating the aluminum, drawing of the vacuum, the mass of OPP and aluminum, and the deterioration of the evaporation boats in which the aluminum is evaporated. All inefficiencies and losses discussed previously were factored in. The final result of the report was that per 1000 kg of metallized OPP produced, 500 kg of CO_2 eq. was released due only to the process electricity (Luhrs, Griffing, Realff, & Overcash, 2010). No other results were discussed. This report is important in that it better represents all of the processes associated with metallization of a polymer. However, as a life cycle inventory, it offers no comparison to aluminum foil as the barrier layer, and it limits the results to CO_2 equivalents. It is used as a reference for developing inventory data, but impacts other than GHG emissions are described for the metallization process. These can be seen in section 7.4.

The reports discussed thus far were not life cycle assessments and many did not include a comprehensive environmental impact study. There are, however, many studies that have focused on more robust environmental assessment of polymer-based flexible food packaging. Common environmental impact categories that are referenced in these reports include acidification, climate change, eutrophication, and fossil fuel depletion (Busser & Jungbluth, 2009; Kliaugaite & Staniskis, 2013; Vidal et al., 2007). Others that have been investigated are ecotoxicity and particulate matter which can affect the human respiratory system. These impact categories, along with the understanding of resource and energy use, help to paint a higher quality picture of the overall life cycle effects of the products.

3.3. Flexible Packaging LCA

3.3.1. Typical Methodology

Life cycle assessment has become a useful tool in evaluating the impact of packaging on the environment. It allows for evaluation of the inputs, outputs, and a range of environmental impacts across the life cycle of a packaging systems (ISO, 2006). Considering the past and expected future growth of flexible packaging (Smithers Pira, 2013), many studies have been conducted using LCA methodology to assess aspects of this packaging genre, specifically multi-layer films. An accepted approach for conducting life cycle assessments is by following the international standards ISO 14040 and ISO 14044 (Kang, Sgriccia, Selke, & Auras, 2013; Kliaugaite & Staniskis, 2013; Siracusa, Dalla Rosa, Romani, Rocculi, & Tylewicz, 2011; Siracusa et al., 2014; Vidal et al., 2007; Xie, Li, Qiao, Sun, & Sun, 2011). These standards establish the guidelines and framework for conducting life cycle assessments (ISO, 2006).

Kliaugaite and Staniskis (2013) compared the life cycle of three different high barrier polymer packaging options using these ISO standards. "The aim of the study was to compare and evaluate environmental burdens associated with raw materials extraction and production of three types of multi-layer gas barrier polymer packaging used for the food industry. A second objective was to assess environmental impact relation to different types of gas barrier layers" (Kliaugaite & Staniskis, 2013). Although their report does not deal with the comparison of metallized polymers and aluminum foil as the barrier layers, the methodology is similar.

The multi-layer packaging films in question were PET-AlOx/LDPE where PET-AlOx is the barrier layer, PET/PE-EVOH-PE where PE-EVOH-PE is the barrier layer, and PET-PVOH/LDPE where the PET-PVOH is the barrier layer. The comparison between barrier layers is accurate because the polymer substrate with which the primary barrier material is bonded is included as a part of the effective barrier layer. In order to fairly compare the alternatives, all three multi-layer films were stated to have the same high barrier value and were all the same thickness. The identical barrier properties allowed the authors to use a functional unit of one square meter for comparison (Kliaugaite & Staniskis, 2013).

The pertinent results are that the PET-AlOx component led to a high impact in the eco-toxicity category due to aluminum mining. It also had significant impacts in mineral consumption, climate change, and fossil fuel use (Kliaugaite & Staniskis, 2013). Aluminum metallized polymers and aluminum oxide polymer films are similar. The major difference is the introduction of oxygen during vaporization which causes aluminum oxide to be transparent (Struller, Kelly, Copeland, & Liauw, 2012).

This study's focus is on that of non-transparent barrier layers, unlike that of Kliaugaite and Staniskis (2013). In packaging scenarios where aluminum foil was historically used as the barrier layer, metallized OPP and metallized PET are the most prevalent replacements (Copeland & Astbury, 2010). This study develops a better understanding of the differences between these three barrier layers and the possible impacts generated from raw materials, production processes, use phase, as well as end of life. Polymers have a high heating value which allow them to produce energy when properly incinerated after use. The use phase and end of life were not explored by Kliaugaite and Staniskis (2013), but both can contribute to a better understanding of the packaging throughout the supply chain.

One other result from Kliaugaite and Staniskis (2013) is that the barrier layer material had significantly less of an environmental impact than the surrounding polymer layers which, depending on the layers, is not the case with aluminum foil as the barrier layer. This does show that each layer of a multi-layer package must be taken into consideration to get a comprehensive understanding of the environmental impacts when comparing barrier layers.

3.3.2. LCA Tools

There are many tools that aid in conducting life cycle assessments such as a wide range of environmental software and life cycle inventory databases. Kliaugaite and Staniskis (2013) used SimaPro software to conduct their assessment, and the ecoinvent database was used for inventory analysis. Another study examined a cradle to factory gate environmental assessment of modified atmosphere packaging in accordance to the ISO standards (Siracusa et al., 2014). Again, SimaPro software and ecoinvent database were used to conduct the study. Both Kliaugaite and Staniskis (2013) and Siracusa et al. (2014) used one square meter of plastic film as a measure of the functional unit and both found that the greatest impact was on resource depletion. Other life cycle analyses of multi-layer packages have been conducted for milk packaging (Xie et al., 2011), bacon packaging (Kang et al., 2013), and for packaging of coffee and butter (Busser & Jungbluth, 2009). Again, all three of these studies used SimaPro to analyze the systems. The assessments conducted by Xie et al. (2011) and Kang et al. (2013) also clearly state the use of ISO standards for their methodology. ISO standards were also used by Vidal et al. (2007) to analyze the environmental impacts of biodegradable versus conventional polymer multi-layer films.

The raw material and processing/manufacturing stages of these studies are always taken into account and contribute to life cycle impacts (Kang et al., 2013; Siracusa et al., 2014; Xie et al., 2011). The transportation phase is not included in studies when products have very similar or the same mass (Kliaugaite & Staniskis, 2013; Vidal et al., 2007). Even when transportation is considered, the impacts associated with it are relatively low in comparison to the impacts from raw materials (Kang et al., 2013; Siracusa et al., 2014; Xie et al., 2011). The use phase is often not included. When comparing packaging laminates, the use phase impacts are null, very similar, or equal. Therefore, they do not contribute to differences when making comparisons (Kliaugaite & Staniskis, 2013; Siracusa et al., 2014). The case study on different coffee packaging alternatives did, however, show that the type of packaging can play a role in how the consumer uses the product, thus contributing life cycle impacts from the use phase (Busser & Jungbluth, 2009). Given the consistency and accuracy of results produced by these studies, similar methodologies are used in the following study and will be discussed further.

4. Problem Statement

Snack food packaging bags, such as those used for potato chips, require high barrier properties. Without proper barrier from external gas, vapor, and ultra-violet light these foods can become stale or rancid. To enable adequate protection, this type of packaging relies on high barrier materials such as aluminum foil, metallized oriented polypropylene (MOPP), or metallized polyethylene terephthalate (MPET) in conjunction with other support material layers. As seen in Figure 3, aluminum foil provides the best range of protection against both water vapor and oxygen gas. However, foil requires significantly more aluminum than the alternatives. With advancements in technology, metallized films such as MOPP and MPET can now provide similar protection to that of aluminum foil at a lower cost and with a reduction of aluminum use. Additional polymer material and associated manufacturing processes are required in order to successfully produce these high barrier metallized films which affect their overall environmental impact.

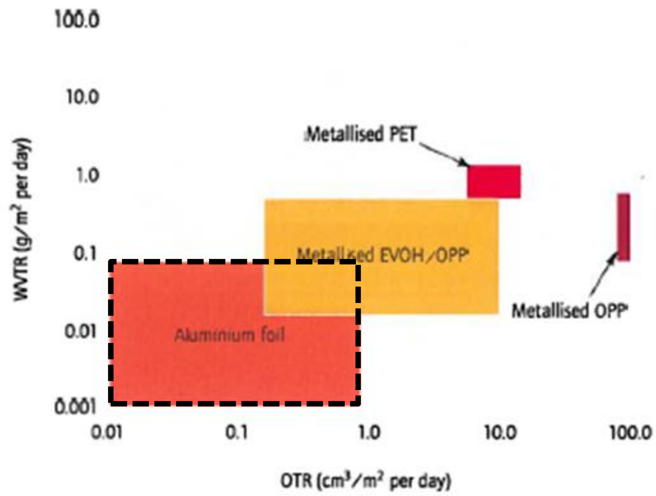


Figure 3 Typical barrier property ranges
Adapted from Petrie (2006)

This study compares the environmental impacts associated with three packaging laminates as follows: PET/AluFoil/LLDPE, PET/MOPP/LLDPE, and PET/MPET/LLDPE (Figure 4). This notation signifies a five layer laminate consisting of the outer printing layer, adhesive, barrier layer, adhesive, and inner sealing layer. The ultimate goal of this study is to determine if

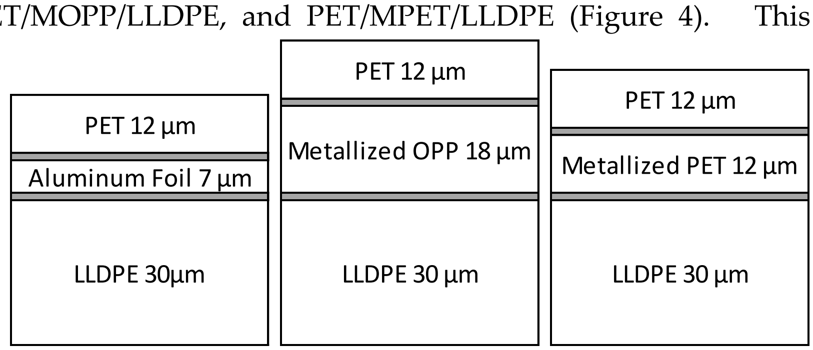


Figure 4 Film compositions

common multi-layer metallized polymer laminates are environmentally beneficial beyond resource and energy reduction compared to aluminum foil laminate and, if so, by how much? The results show which of these three laminates is the least environmentally impactful for use in packaging of snack foods based primarily on the barrier layers. The functional unit and methodology used for this comparison will be discussed in detail in section 6.

5. Purpose

The purpose of this research is to analyze and provide a more in depth understanding of the environmental impacts associated with metallized OPP and metallized PET films compared to aluminum foil when used as the barrier layer of multi-layer flexible packaging. Other materials such as ethylene vinyl alcohol (EVOH) and nylon offer good barrier properties as well, but PET and OPP are the most widely used films for this type of packaging application (Copeland & Astbury, 2010), and is why they are analyzed in this study. These alternatives are compared while having similar layering in order to determine which is least impactful to the environment overall.

There is no readily available research that shows a comprehensive assessment of the environmental effects of these films compared to aluminum foil when used in a laminated package. This study fills this gap in literature and provides a more thorough understanding of these aluminum-based barrier layer as well.

6. Methodology

To compare these packaging laminates, Microsoft Excel is used to collect, organize, and manipulate data and display graphical results. SimaPro version 8 is the program through which the environmental analysis is performed. CES EduPack 2014 is used as a means of providing reference to material and process data to be used in the SimaPro inventories. These tools and the methodology standards set by the International Organization for Standardization (ISO) allow for a standardized approach for completing the environmental analysis. These international standards include the ISO 14040:2006 and the ISO 14044:2006 which layout the framework and guidelines for completing life cycle assessments (ISO, 2006). This study is not peer reviewed, as required by guidelines, and therefore is not a life cycle assessment. It is strictly referred to as an environmental analysis using the LCA framework as a guide.

6.1. Framework

The ISO framework for conducting life cycle assessments consists of four main procedures. These are the goal and scope definition, inventory analysis, impact assessment, and interpretation. Interpretation happens throughout the entire analysis and the process is iterative (Figure 5).

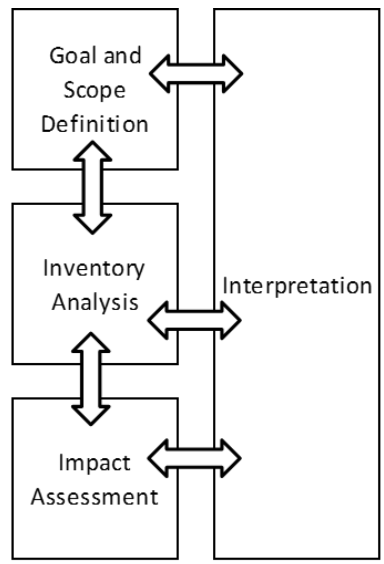


Figure 5 ISO LCA framework from Baumann & Tillman (2004)

6.1.1. Goal and Scope Definition

The goal definition must state the intended application of the study, reasons for carrying it out, and the intended audience. Defining the scope of the study consists of selecting the options to model, defining the functional unit, choosing of impact categories and method for impact assessment, and establishing system boundaries (Baumann & Tillman, 2004). The goal of this study is to compare the three previously mentioned aluminum-based multi-layer packaging alternatives to determine the environmental impacts of each. The results of the study are intended for use by packaging professionals in academia and industry to aid in a better understanding of the environmental implications due to material choice.

6.1.1.1. Functional Unit

When performing an environmental analysis on the life cycle of products or systems, an equivalent function is the basis for fair comparison. In the case of food packaging, this function is to protect and preserve the food, thus reducing losses. In order to accurately compare differing food package technologies, the ability of the packaging to accomplish this function determines the functional unit of the life cycle study. For multi-layer flexible packages, such as potato chip bags, the ability to retain food freshness is primarily based on three properties: oxygen transmission rate ($cm^3/m^2/day$), water vapor transmission rate ($g/m^2/day$), and optical density. OTR and WVTR requirements were previously discussed, but optical density, or OD, represents the ability of light to pass through a material layer. According to Decker et al. (2004), an OD of around 2.3 to 2.5 is sufficient for almost all food applications. It is worth nothing that the MPET film has an OD of 2.2 which is very near the referenced range. The other options meet this criteria. All three of these properties play a role in protecting the food inside, but the oxygen transmission is of utmost importance.

Most of the reactions that degrade the quality of the food in the packaging are due to the presence of oxygen (PolyPrint Inc., 2008). The oxygen barrier retains a low concentration of oxygen within the sealed packaging and is defined as high barrier material if the OTR is less than approximately 10 $cm^3/m^2/day$ (FFPC, 2011; PolyPrint Inc., 2008). As seen in Table 1, the barrier layer alone for each alternative meets this requirement, and only improves with the addition of surrounding layers. Defining all three laminates as 'high barrier', due to their ability to meet this requirement for food protection, allows for equal comparison. Therefore, a functional unit of one square meter of laminated film is used for this study. All associated life cycle inventory data used in the model and results are based around this functional unit.

Table 1 Barrier property values

	Aluminum Foil	MOPP	MPET	Units
OTR	~0.1	8.53	0.6	$cm^3/m^2/day$
WVTR	~0.01	0.062	0.6	$g/m^2/day$

6.1.1.2. Scope

The primary focus of this study is that of the raw materials and the manufacturing/processing associated with the alternative technologies. The use phase is considered in part to determine the potential reduction in barrier capabilities due to theoretical shipping and handling of the packages through the supply chain as well as how different size packages may influence consumer choice. The use phase is not modelled in the environmental software, but is discussed to aid in the interpretation and conclusions. The disposal phase is analyzed due to the differing masses and thicknesses of the various materials per alternative. See Figure 6 for a high level

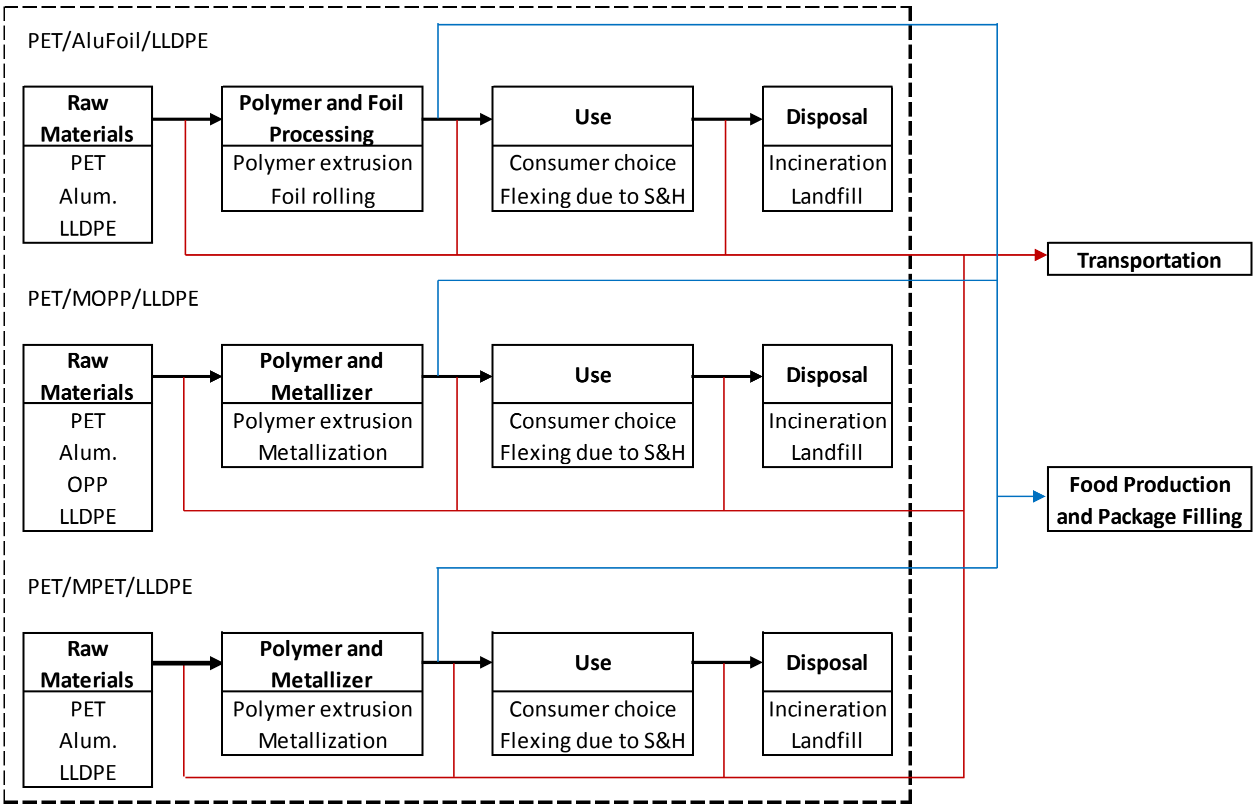


Figure 6 System boundary

overview of the life cycle stages that are and are not analyzed. The dotted line in the figure represents the boundary of the system.

Food production and package filling as well as transportation are not included in this study. Food production and package filling will be similar for each alternative and will offer no pertinent insight into differing environmental impacts. There is no specialized transport required for any of the laminates and the total mass difference between the heaviest and lightest laminate is less than 4.4% in this case. Considering that transportation is measured in mass*distance units in environmental software, the minimal difference in masses and no need for specialized transport suggest that it can be disregarded for this analysis. Including transportation would lead to slightly more accurate results, but it will not be evaluated in this study.

6.1.1.3. Impact Categories

The primary results of the study are expressed as overall environmental impact (ecopoints), global warming potential (kg CO_2 eq.), and embodied energy (kWh). An ecopoint is a measure of the overall environmental impact stemming from a material, process, or service (Edge Environment). It is more accurately defined as one thousandth the annual environmental impact of an average person living in the European Union (BSRIA, 2012), and is the summation of categories mentioned earlier including ozone depletion, human toxicity, particulate matter, and fossil depletion to name a few. This result is generated via the impact assessment method ReCiPe Endpoint (H) in SimaPro. This is the hierarchist method and represents an average weighting of impacts. The global warming potential (GWP) of a material, process, or service is expressed as kg of CO_2 eq. This result is generated using the IPCC 2007 GWP 100a method. This expresses the climate change potential of a material, process, or service over a 100 year timespan. Finally, the embodied energy of a product or service is the total energy associated with the life cycle and is expressed in kilowatt hours (kWh). This is generated via the Cumulative Energy Demand version 1.08 method. These impact categories together generate a complete environmental impact summary of aluminum foil, metallized OPP, or metallized PET laminated films. Bar graphs are used for this comparison. These graphs are primarily created in Excel from the output data of SimaPro.

6.1.2. Inventory Analysis

The inventory analysis is the step in which the relevant inputs and outputs of the system described by the goal and scope are collected. A flow chart, as seen in Figure 6, is necessary for this step to allow for a visualization of the system and its boundaries. More detailed system flow diagrams for each laminate can be found in the Appendix. The data pertaining to each system's inputs and outputs is collected, normalized to fit the functional unit, and used to determine the associated environmental loads (Baumann & Tillman, 2004). Much of this process is simplified through the use of SimaPro.

Inventory data, and associated mass and energy flows, are already available through the databases in SimaPro. The database that is most frequently utilized is ecoinvent version 2.2. This database was created by the Swiss Centre for Life Cycle Inventories (ecoinvent, 2010). The selection of materials and processes are made within this database and related to the functional unit of one square meter of laminated film. When specific materials and processes are not available within the database, they are manually created to depict the process as accurately as possible. This is the case with the process of metallizing a polymer web, for instance. All assumptions are stated clearly, specifically for said process, so as to promote transparency of the study.

6.1.3. Impact Assessment

The environmental impacts that are generated by the system are described in the impact assessment. The sole reason for this step is to make the results easier to understand and communicate to the intended audience (Baumann & Tillman, 2004). There are three general divisions of environmental impact which are resource use, human health, and ecological consequences. Within these divisions are some impact categories such as global warming, acidification, energy and material depletion, and human toxicity. As previously stated, this impact assessment includes the global warming potential, embodied energy, and ecopoints of each laminate. SimaPro's method for calculating this score (ReCiPe Endpoint) classifies the parameters according to their environmental impact, characterizes the contribution of the environmental loads to an impact type, and uses a weighting scheme to develop the final score. The weighting for this particular method is 40/40/20 for human health, ecological consequences, and resource use, respectively (Baumann & Tillman, 2004).

6.1.4. Interpretation

In the interpretation phase, results are assessed and conclusions are drawn. The simplest way to present these results is with the use of charts and diagrams (Baumann & Tillman, 2004). SimaPro produces graphs to show results of a study, but they are usually not easily formatted. If formatting these graphs is not necessary, they are used directly from SimaPro. Results that require formatting are exported to Microsoft Excel to produce graphs that convey all necessary information in a user-friendly layout. The interpretation phase also includes a sensitivity analysis to check the effect of critical data on the results (Baumann & Tillman, 2004).

6.1.4.1. Sensitivity Analysis

For a better understanding of how the inventory data affects the results, a basic sensitivity analysis is performed. Initial results of the study showed that raw materials and processing are the largest contributors to impacts. For this reason, the sensitivity analysis primarily focuses on these factors. The first case tests possible variability in the rolling of aluminum foil process from the IDEMAT database. This is the only data not taken from the ecoinvent database, and testing its influence is necessary. A change of -20% in electricity consumption is used to test how the impacts vary, and to see if it brings the foil laminate within range of the impacts associated with the metallized films.

A similar approach is taken for the metallization process. The data received from Bobst Manchester Ltd only represents a single standard pitch machine. The size of the machine, electricity consumption, and amount of material processed is assumed to be directly related. To test for possible variances the electricity consumed is altered +20% from the base case. Also, the grid mix is tested for influence as well. A grid mix representing a United States average and one representing a European average are both analyzed to determine the sensitivity of where these machines are operated.

The disposal scenario is altered to determine the sensitivity of end of life treatment options. A split of 80% to landfill and 20% to incineration represents disposal within the United States. A 50/50 split better represents that of Europe. If properly incinerated at a facility that recovers the energy, a disposal scenario with greater incineration may be beneficial. This is discussed further in section 7.5.3.1.

6.2. Materials

A bill of materials was given for each laminate as previously seen in Figure 4. The material composition and thicknesses were known. In order to enter the material data into SimaPro, the thicknesses were converted to masses. SimaPro handles material inputs as masses, which must correlate with the established functional unit (one square meter of laminated film in this case). In order to convert film thickness to mass, the volume of each individual layer was calculated and multiplied by its respective density. See Table 2 for material parameters.

Table 2 Material parameters

Parameter	Quantity	Unit	Reference
Film Area	1	m^2	User defined
Aluminum Density	2700	kg/m^3	CES EduPack 2014
LLDPE Density	929	kg/m^3	CES EduPack 2014
PET Density	1340	kg/m^3	CES EduPack 2014
OPP Density	902	kg/m^3	CES EduPack 2014
Vaporized Alum. Thickness	50	nm	Manuf. Spec. Sheet
Foil Thickness	7	µm	
MOPP Total Thickness	17.8	µm	
MPET Total Thickness	12	µm	
PET Thickness	12	µm	
LLDPE Thickness	30	µm	

The densities are average values taken from CES EduPack 2014 software for the aluminum and polymer materials (Granta Design Ltd, 2014). The foil thickness is 7 µm which is typical and the vaporized aluminum thickness is 50nm, which is a typical thickness based on the metallization process capabilities (Barlow, 2015; Bishop, 2007). The thickness of the MOPP is 18 µm, and the thickness of the MPET is 12µm from respective specification sheets. Each alternative has a PET layer specified at 12 µm and a LLDPE layer specified at 30 µm. Based on the material parameters and packaging specifications, the raw material input masses per square meter of film can be seen in Table 3 for each layer as well as for the PVD Inefficiency and Evaporation Boats. The physical vapor deposition (PVD) inefficiency represents the mass of the typical aluminum overspray during the metallization process. Raw materials were assumed to be virgin material and were entered as such into the SimaPro model.

Table 3 SimaPro material inputs (g)

Description	Material	Quantity
Foil	Aluminum	19.184
MOPP	Aluminum	0.135
	PP	16.387
MPET	Aluminum	0.135
	PET	16.390
Outer Layer	PET	16.475
Inner Layer	LLDPE	28.555
PVD Inefficiency	Aluminum	0.135
Evaporation Boats	Boron Nitride	1.12E-09
	Titanium Diboride	1.12E-09

The values seen in Table 3 also take into account any material waste associated with respective manufacturing processes like foil rolling and polymer extrusion. The masses associated with the materials that make up the laminates were also used as a means to justify disregarding transportation for this study.

6.2.1. Transportation

Transportation was disregarded for this study for three reasons. The first is that no specialized transportation is required for these laminates. The second reason is that exact transportation routes for packaging products such as these are not necessarily easy to determine. They vary depending on where the product is being shipped to and from. Lastly, the masses of the three alternatives are very similar. SimaPro calculates impacts associated with transportation based on a mass*distance unit (e.g. kg*km). Since the masses are so similar, the transportation phase would not offer significant impact differences amongst the laminates, especially with uncertainty in the exact transportation routes and distances. See Table 4 for reference of masses per square meter of film and differences among each alternative.

Table 4 Mass of layers

	Outer Layer		Functional Barrier Layers		Inner Layer		Total Weight (g)	
PET/Alu Foil/LLDPE	PET Layer		Aluminum Foil Layer		LLDPE Layer			
	PET Mass (g)	16.08	Foil Mass (g)	18.90	LLDPE Mass (g)	27.87		62.85
							% less than heaviest	0.000
PET/MOPP/LLDPE	PET Layer		Metallized OPP Layer		LLDPE Layer			
	PET Mass (g)	16.08	OPP Mass (g)	16.011	LLDPE Mass (g)	27.87		60.096
			Aluminum Mass (g)	0.135			% less than heaviest	4.383
				16.146				
PET/MPET/LLDPE	PET Layer		Metallized PET Layer		LLDPE Layer			
	PET Mass (g)	16.08	PET Mass (g)	16.013	LLDPE Mass (g)	27.87		60.098
			Aluminum Mass (g)	0.135			% less than heaviest	4.379
				16.148				

6.3. Manufacturing Processes

There are two primary manufacturing processes that are addressed in this study. These are the rolling of aluminum foil and the metallization of polymer webs. The environmental impacts associated with these processes is one of the biggest differences between alternatives, other than material use. The process of foil rolling involves loading an ingot of aluminum into a rolling machine in which heavy rollers press the ingot. The distance between the rollers is decreased each pass to slowly roll out the aluminum ingot into a foil (Emblem & Emblem, 2012). The foil is annealed after rolling to restore ductility to the material (Aluminum Association, 2008). This process was accessed through the IDEMAT 2001 database in SimaPro. This database was developed at Delft University of Technology and focuses on the production of materials (Delft University of Technology, 2001). This is the only process referenced in this study not taken from ecoinvent. See Table 5 for all process inputs per square meter of film.

Table 5 SimaPro process inputs

Layer	SimaPro Process	Quantity	Unit
Foil	Rolling aluminum foil I	19.184	g
MOPP	Section bar extrusion	0.270	g
	Extrusion, plastic	16.387	g
	Electricity, high voltage	0.01815	MJ
MPET	Section bar extrusion	0.270	g
	Extrusion, plastic	16.390	g
	Electricity, high voltage	0.01815	MJ
Outer PET	Extrusion, plastic	16.475	g
Inner LLDPE	Extrusion, plastic	28.555	g

The process of metallizing a polymer web is not available within the software and, therefore, is manually created based on collected data. The SimaPro processes, seen in Table 5, representing the creation of a metallized polymer include section bar extrusion, plastic extrusion, and electricity. The section bar extrusion is the ecoinvent process used to represent the production of the aluminum wire that is vaporized during the metallization process. The plastic extrusion is the process of converting polymer resin into a sheet format. The electricity is representative of the energy consumed by the metallizing machine during a typical cycle outlined in Table 6. This electrical energy consumption comes from warming up the machine, producing a vacuum, running the chiller, resistance heating the boats, translating the web, unrolling the aluminum wire, and defrosting the machine interior after metallization of the web. Average metallization processing data was collected from Bobst Manchester Ltd, a machinery supplier, for use in this study. See Table 6 for metallization energy data.

The collected metallization data includes the amount of material processed by the machine, the stand-by time and power, the pump-down time and power, the metallizing time and power, and the defrost time and power. Stand-by is when the machine is cleaned and prepped for another metallization cycle. Pump-down is the machine drawing an adequate vacuum to enable vaporization of the aluminum, and metallization is the process of heating the boats, feeding the aluminum wire, translating the polymer roll, etc. (Bobst Manchester Ltd, 2015). Defrost is the process of bringing the cooling system back up to a temperature above the dew point so that condensation does not form on all surfaces when the machine is re-opened to the atmosphere (Bishop, 2015).

Table 6 Metallization energy data
(collected from Bobst Manchester Ltd)

Description	Quantity	Unit		Process Energy	Unit
Material processed	156240	m^2			
Stand-by time	0.25	hr			
Pump-down time	0.15	hr			
Metallizing time	1.2	hr			
Defrost time	0.08	hr			
Total cycle time	1.7	hr			
Stand-by power	140.73	kW			
Pump-down power	208.93	kW			
Metallizing power	587.11	kW			
Defrost power	198.74	kW			
Stand-by energy	35.2	kWh	=	0.00081	MJ/m^2
Pump-down energy	31.3	kWh	=	0.00072	MJ/m^2
Metallizing energy	704.5	kWh	=	0.01623	MJ/m^2
Defrost energy	16.6	kWh	=	0.00038	MJ/m^2
		Total energy	=	0.01815	MJ/m^2

These values were then converted to average energy consumption per phase, summed, and normalized to energy per square meter (See section 12.8.1 for calculations). The results are that 0.01815 MJ/m^2, or 0.00504 kWh/m^2, are required during the entire process to produce a square meter of metallized polymer barrier layer film.

This energy figure is used to generate a part of the inventory for the metallization process within the SimaPro software. The 50% overspray associated with the process is also inventoried; that aluminum material is collected and recycled from the metallizing machine in order for it to continue to run properly (Barlow, 2015; Bobst Manchester Ltd, 2015). Finally, data associated with the evaporation boats was collected and allocated to fit the functional unit so that the environmental impacts associated with the metallized polymers may be more accurate.

The evaporation boats consist of about 50% titanium diboride and 50% boron nitride and each boat has a service life of around 15 hours (Bobst Manchester Ltd, 2015). Data collected from the CES EduPack 2014 software on the carbon dioxide and NOx production associated with these boat materials is inventoried in the SimaPro software (Granta Design Ltd, 2014). See Table 7 for the collected evaporation boat data used for this study.

Table 7 Evaporation boat data

Mass of one boat	0.132	kg
# of boats	33	
Boat life span	15	hrs
	Titanium Diboride	Boron Nitride
Compostion	0.5	0.5
Mass (kg)	0.066	0.066
$CO_{2\,eq.}$ (kg/kg)	4.83	6.82
Nox (kg/kg)	0.02685	0.0379
End of Life	Landfill	
Consumed average (kg/m^2)	2.23E-06	

The mass of one boat was assumed to be 132 grams (Bishop, 2015). The particular metallizing machine referenced in this study operated with 33 evaporator boats. Using these figures, the amount of material processed by the machine (as shown in Table 6), and assuming that the environmental impacts of the boats are directly allocated to the metallized polymer, the normalized rate of boat consumption is 2.23E-6 kg/m^2 of metallized film (See section 12.8.2 for calculations).

6.4. Use Phase

The use phase of packaging laminates such as these is essentially comprised of shipping and handling. Once the sealed package is opened by the end user, the barrier properties play a less significant role due to exposure to ambient conditions. This means that the ability of the package to protect the food comes more into play during the distribution of the product. During distribution, these packages are handled by a range of individuals and can wear due to flexing. This wear can affect the barrier properties of the package.

Figure 7 Gelbo flex tester

In an attempt to simulate how these three packaging laminates stand up to the wear associated with shipping and handling, all three are flexed on a Gelbo Tester (Figure 7). Prior to flexing, all three laminates are tested for both gas and water vapor transmission with permeability test machines as a baseline. After obtaining baseline values for each, fresh samples of each are cut into 200 by 280 mm sheets and loaded into the machine. One flex cycle consists of a twisting motion of 440° over a distance of 90 mm followed by a horizontal pressing motion over 65 mm at a rate of 45 cpm (ASTM International). Condition D, full flex for 20 cycles, is used for this study and is typically used for evaluating the effect of flexing on gas and water vapor transmission rates. Results from OTR measurements that were taken before and after flexing show that each laminate maintains its high barrier capabilities (See section 7.7.2.). Since flexing does not alter the barrier capabilities of the laminates beyond the limit established by the functional unit, it is deemed not to contribute to environmental impacts.

One other part of the use phase that was investigated is consumer choice associated with purchase of either large family-sized laminate bags or smaller individual-sized laminate bags of these materials. Consumer behavior is a challenging aspect of sustainability, especially in the packaging field. Measurements of four samples from each size bag were taken and used to produce a recommendation to consumers of one way to influence lower environmental impacts. See section 7.7.1. for further explanation and results of this.

As stated, the results from these use phase data are not used in the SimaPro model, but are meant to add pertinent information to the interpretation and recommendations of the study.

6.5. End of Life

From the perspective of a consumer, the most-likely end of life scenario for these packages is disposal into the municipal waste stream without any recovery/recycling. Supporting this assumption are the findings in a report prepared for the American Chemistry Council and The Canadian Plastics Industry Association by Franklin Associates. According to this report, the recovery rates of materials used in converted flexible packaging is negligible: LDPE - 0%, PET – 0%, aluminum – 0%, and PP – 1.80% (Franklin Associates, 2014). Due to the laminated layering of these packages, separation of materials is not easy which poses problems for recycling. Pyrolysis is a recycling technology that can handle multi-layer packaging, but it is not yet readily available within the United States. Also, these packages are not labeled in any way that informs the consumer of recycling options. All of this entails that final processing will occur via landfill and incineration; no consideration of the effects of litter is made in this study.

Table 8 Energy content of plastics Adapted from Andrady & Neal (2009) and Themelis, Castaldi, Bhatti, & Arsova (2011)

Material	Heating Value [MJ/kg]
PP	46
PE	46
PET	25
Paper	16
Wood	18
U.S. Coal	13

According to a report by the United States Environmental Protection Agency, about 80% of municipal solid waste goes to landfill and the other 20% is incinerated with energy recovery (US EPA, 2014). This ratio is used to create the end of life scenario for these packaging alternatives. As landfill space decreases, more material may be directed toward incineration. Also, plastics have a relatively high energy content. Recovery of this energy could be beneficial (Table 8). For those reasons, a 50/50 landfill to incineration ratio will be used to test the effects of the end of life scenario on the results. This is approximately the ratio of landfill to incineration in Europe (Eurostat, 2012). Credits due to energy recovery from incineration, and from recycling of the aluminum overspray during metallization, are not allocated to this system, but will be discussed. With all life inventory compiled and normalized to the functional unit of one square meter of laminated film, results were generated.

7. Results and Discussions

All results are defined by the functional unit of the system. Therefore, all values represent the potential impacts associated with one square meter of laminated film.

7.1. Aluminum Foil Laminate

7.1.1. Total Impact

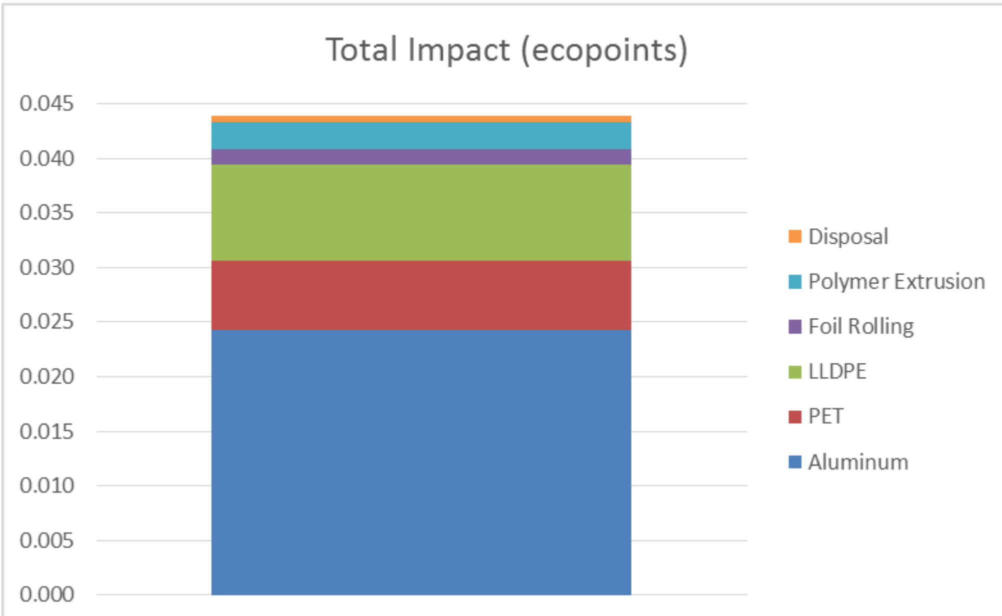


Figure 8 Foil laminate total impact

Table 9 Foil laminate impact breakdown

Phase	Description	Value (ecopoint)	Percentage	
Raw Materials	Aluminum	0.0243	55.33%	89.87%
	PET	0.0063	14.32%	
	LLDPE	0.0089	20.22%	
Processing	Foil Rolling	0.0014	3.07%	8.65%
	Polymer Extrusion	0.0025	5.58%	
End of Life	Disposal	0.0006	1.48%	1.48%
	Total	**0.0439**		

For the aluminum foil laminate, the raw materials contribute the largest impact among life cycle phases at 89.87%. The aluminum contributes the most at 55.33% of all impacts across the life cycle. The total impact of the aluminum foil laminate is 0.0439 ecopoints. See Figure 8 and Table 9 for further breakdown of these results.

7.1.2. Global Warming Potential

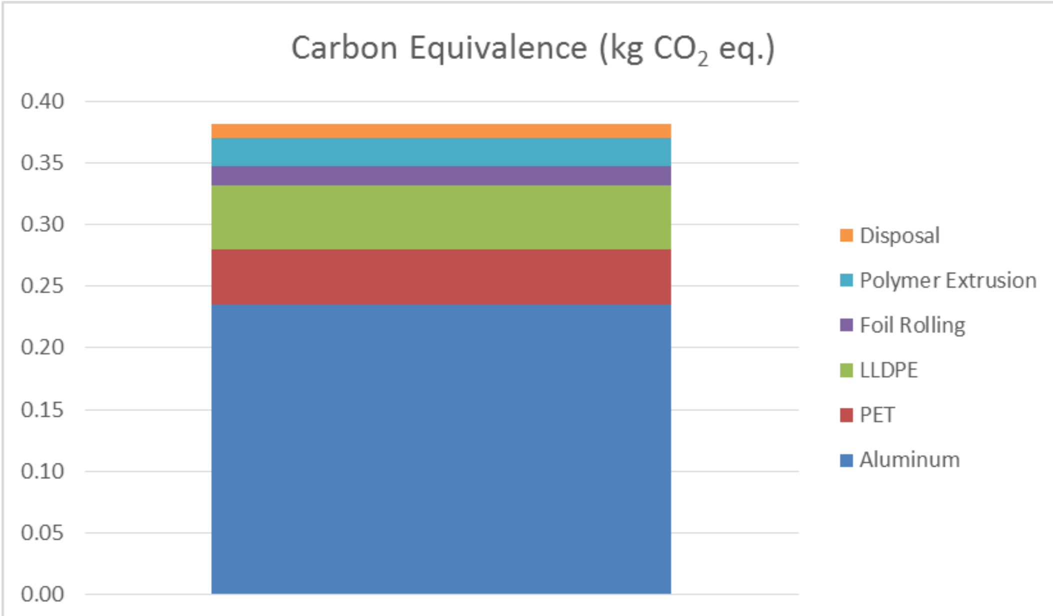


Figure 9 Foil laminate GWP

Table 10 Foil laminate GWP breakdown

Phase	Description	Value (kg CO_2 eq.)	Percentage	
Raw Materials	Aluminum	0.235	61.58%	87.05%
	PET	0.044	11.64%	
	LLDPE	0.053	13.84%	
Processing	Foil Rolling	0.015	3.90%	10.09%
	Polymer Extrusion	0.024	6.18%	
End of Life	Disposal	0.011	2.86%	2.86%
	Total	**0.382**		

Raw materials contribute to the largest global warming potential at 87.05% of all life cycle phases. Again, the aluminum contributes a significant quantity of carbon dioxide at 0.235 kg CO_2 eq., which is 61.58% of the life cycle impact. The total GWP of the aluminum foil laminate is 0.382 kg CO_2 eq. See Figure 9 and Table 10 for further breakdown of these results.

7.1.3. Embodied Energy

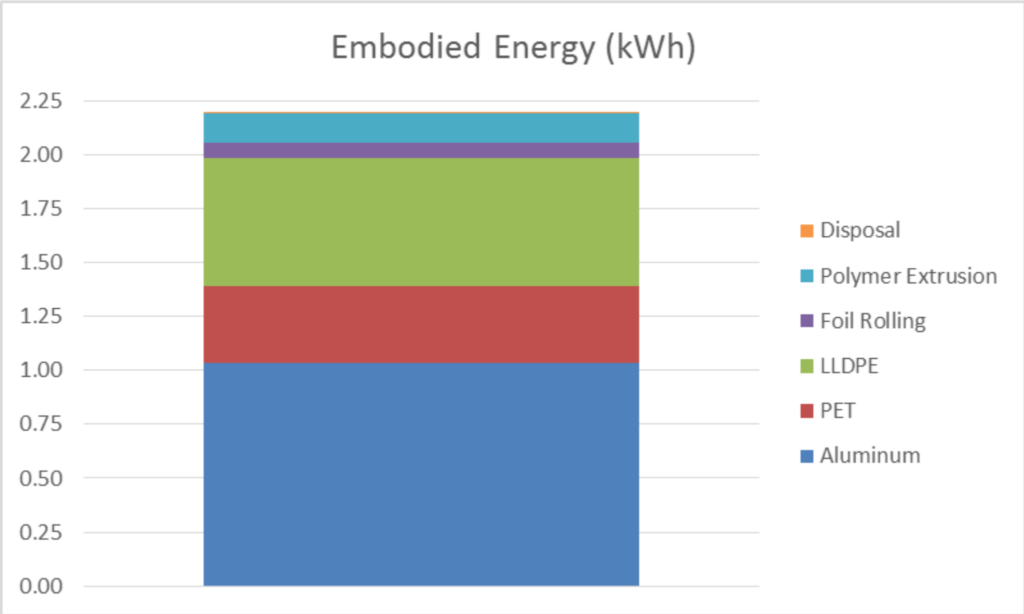


Figure 10 Foil laminate embodied energy

Table 11 Foil laminate embodied energy breakdown

Phase	Description	Value (kWh)	Percentage	
Raw Materials	Aluminum	1.033	47.03%	90.27%
	PET	0.358	16.31%	
	LLDPE	0.592	26.93%	
Processing	Foil Rolling	0.075	3.40%	9.62%
	Polymer Extrusion	0.137	6.22%	
End of Life	Disposal	0.002	0.11%	0.11%
	Total	**2.197**		

Raw materials contribute to just over 90% of embodied energy associated with the life cycle phases. Aluminum contributes the most to this at 47% of all processes. The total embodied energy of the aluminum foil laminate is 2.197 kWh. See Figure 10 and Table 11 for further breakdown of these results.

7.2. MOPP Laminate

7.2.1. Total Impact

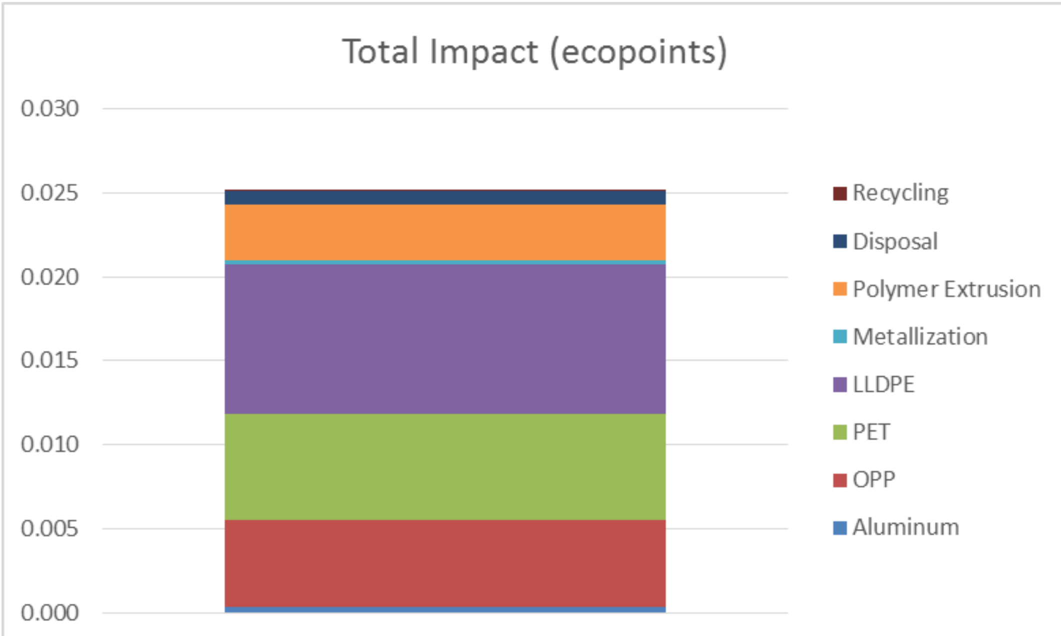


Figure 11 MOPP laminate total impact

Table 12 MOPP laminate impact breakdown

Phase	Description	Value (ecopoint)	Percentage	
Raw Materials	Aluminum	0.00034	1.36%	82.24%
	OPP	0.00519	20.62%	
	PET	0.00629	24.99%	
	LLDPE	0.00888	35.28%	
Processing	Metallization	0.00029	1.15%	14.46%
	Polymer Extrusion	0.00335	13.31%	
End of Life	Disposal	0.00081	3.21%	3.30%
	Recycling	0.00002	0.10%	
	Total	**0.0252**		

For the MOPP laminate, raw materials contribute the most to total impacts at 82.24% of all phases. The inner LLDPE layer has the highest impact at just over 35% of all processes, followed by the outer PET layer at 25%. The quantity of aluminum is so small that it only makes up 1.36% of the impact, but the OPP on which it is deposited makes up just over 20% of the total impacts. The overall impact of the MOPP laminate is 0.0252 ecopoints. See Figure 11 and Table 12 for further breakdown of these results.

7.2.2. Global Warming Potential

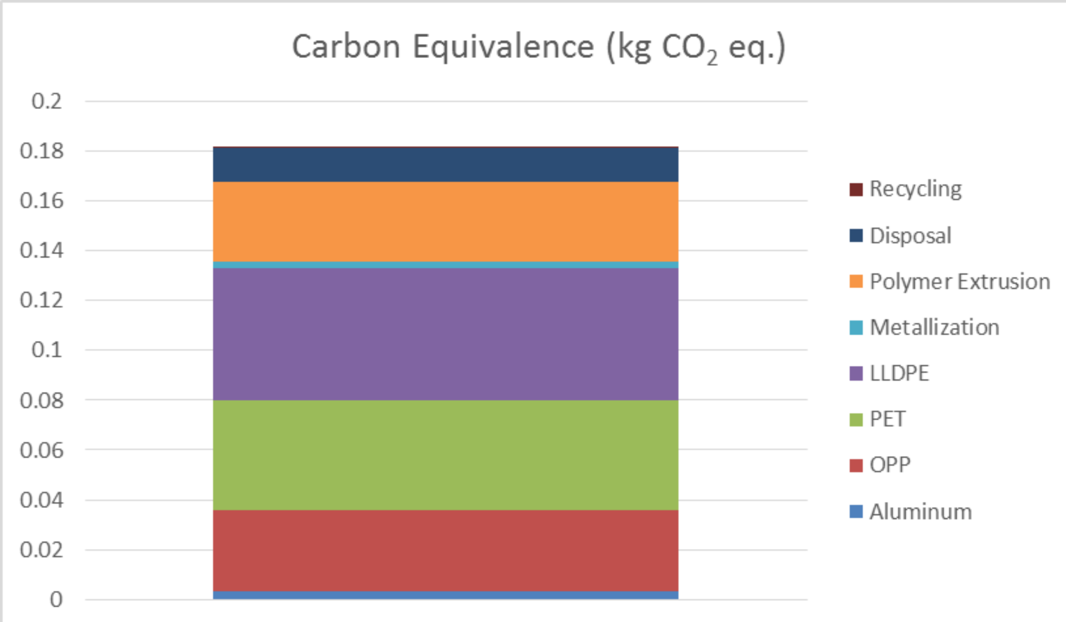


Figure 12 MOPP laminate GWP

Table 13 MOPP laminate GWP breakdown

Phase	Description	Value (kg CO_2 eq.)	Percentage	
Raw Materials	Aluminum	0.0033	1.81%	73.08%
	OPP	0.0324	17.82%	
	PET	0.0444	24.42%	
	LLDPE	0.0528	29.03%	
Processing	Metallization	0.002768	1.52%	19.23%
	Polymer Extrusion	0.0322	17.71%	
End of Life	Disposal	0.0138	7.59%	7.69%
	Recycling	0.000186	0.10%	
	Total	**0.182**		

Raw materials contribute to the largest GWP for the MOPP laminate at just over 73%. The inner LLDPE layer has the greatest GWP at 29%, followed by the outer PET layer at 24.4%. THE GWP associated with processing is more significant due to the three polymer layers that all require this step. The total GWP for the MOPP laminate is 0.182 kg CO_2 eq. See Figure 12 and Table 13 for further breakdown of these results.

7.2.3. Embodied Energy

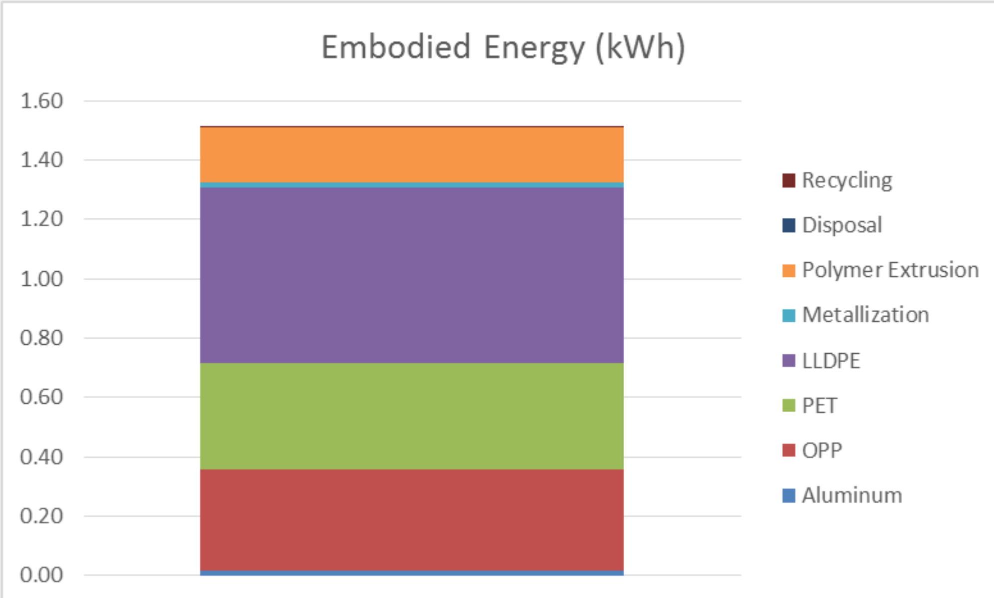


Figure 13 MOPP laminate embodied energy

Table 14 MOPP laminate embodied energy breakdown

Phase	Description	Value (kWh)	Percentage	
Raw Materials	Aluminum	0.015	0.96%	86.38%
	OPP	0.342	22.60%	
	PET	0.358	23.70%	
	LLDPE	0.592	39.13%	
Processing	Metallization	0.017	1.11%	13.43%
	Polymer Extrusion	0.186	12.33%	
End of Life	Disposal	0.002	0.12%	0.18%
	Recycling	0.001	0.06%	
	Total	**1.512**		

The raw materials contribute to the largest embodied energy of all phases at 86.4% with the LLDPE inner layer at just over 39%. The total embodied energy for the MOPP laminate is 1.512 kWh. See Figure 13 and Table 14 for further breakdown of these results.

7.3. MPET Laminate

7.3.1. Total Impact

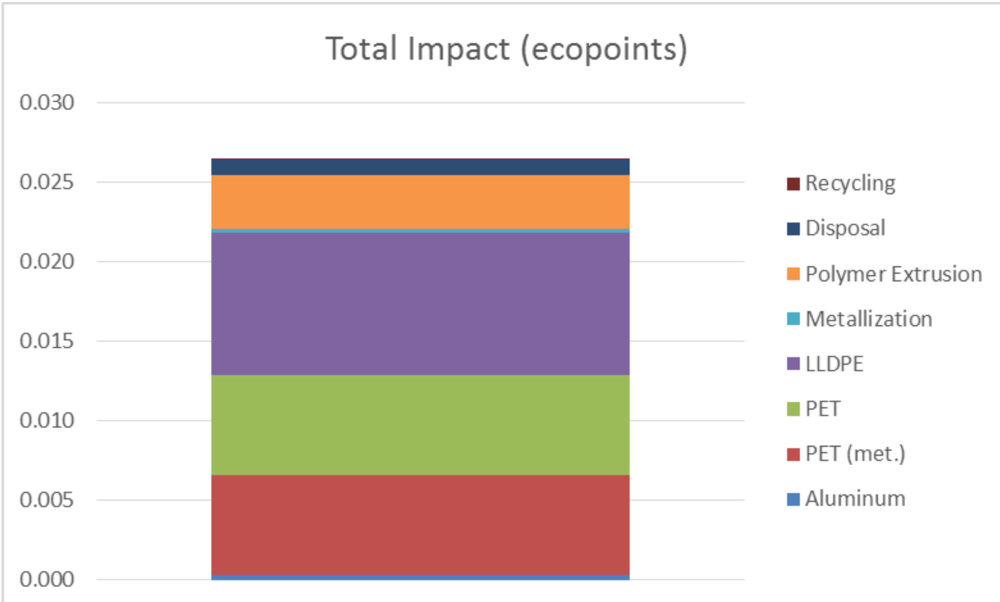


Figure 14 MPET laminate total impact

Table 15 MPET laminate impact breakdown

Phase	Description	Value (ecopoint)	Percentage	
Raw Materials	Aluminum	0.00034	1.29%	82.35%
	PET (met.)	0.00629	23.76%	
	PET	0.00629	23.76%	
	LLDPE	0.00888	33.54%	
Processing	Metallization	0.00029	1.09%	13.75%
	Polymer Extrusion	0.00335	12.65%	
End of Life	Disposal	0.00101	3.81%	3.91%
	Recycling	0.00002	0.09%	
	Total	**0.0265**		

The raw material phase contributes to the largest impacts at 82.35%, compared to other phases. The inner LLDPE layer contributes the most to this, followed by the two PET layers. The total impacts of the MPET laminate is 0.0265 ecopoints, which is slightly larger than that of the MOPP laminate. See Figure 14 and Table 15 for further breakdown of these results.

7.3.2. Global Warming Potential

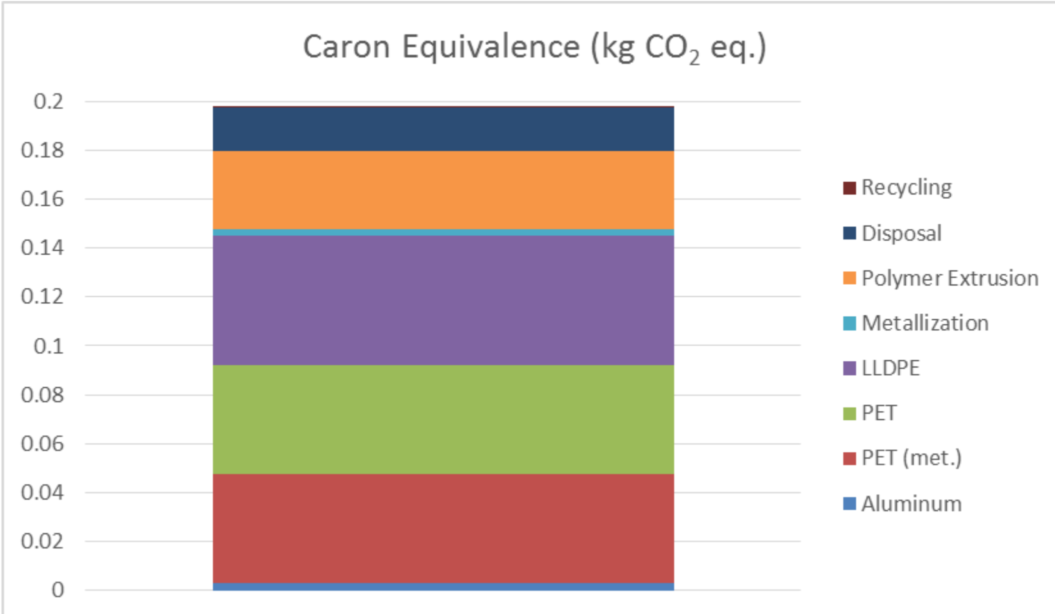


Figure 15 MPET laminate GWP

Table 16 MPET laminate GWP breakdown

Phase	Description	Value (kg CO_2 eq.)	Percentage	
Raw Materials	Aluminum	0.0033	1.67%	73.37%
	PET (met.)	0.04435	22.47%	
	PET	0.04435	22.47%	
	LLDPE	0.0528	26.75%	
Processing	Metallization	0.002768	1.40%	17.72%
	Polymer Extrusion	0.0322	16.32%	
End of Life	Disposal	0.0174	8.82%	8.91%
	Recycling	0.000186	0.09%	
	Total	**0.197**		

The raw materials phase makes up the largest quantity of carbon equivalence at 73.37%, followed by the processing phase mostly due to the film extrusion. Again, the inner and outer layers contribute the most to the raw material phase, more so than the metallized polymer materials. The total global warming potential for the MPET laminate is 0.197 kg CO_2/kg. See Figure 15 and Table 16 for further breakdown of these results.

7.3.3. Embodied Energy

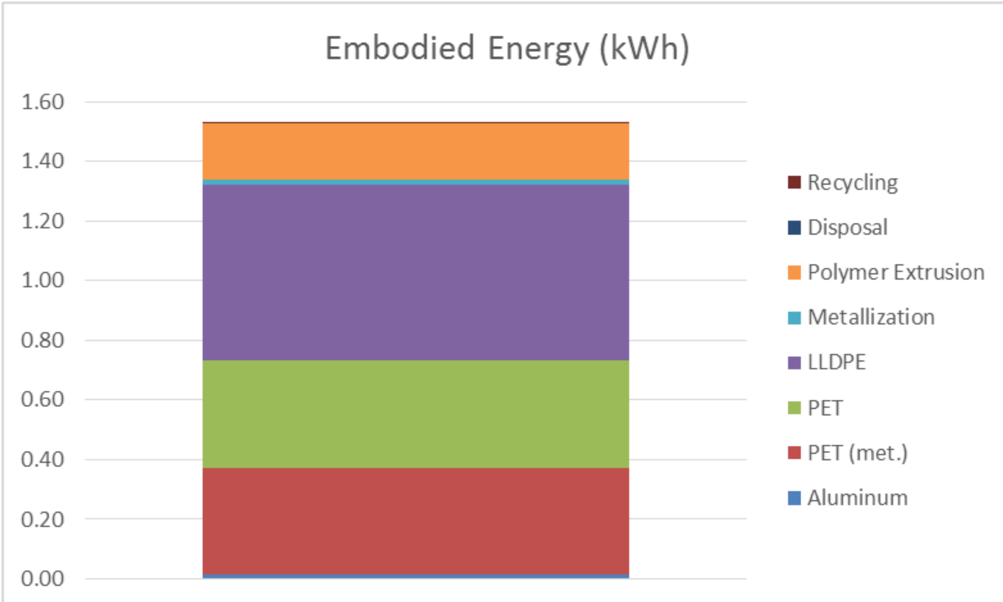


Figure 16 MPET laminate embodied energy

Table 17 MPET laminate embodied energy breakdown

Phase	Description	Value (kWh)	Percentage	
Raw Materials	Aluminum	0.015	0.95%	86.49%
	PET (met.)	0.358	23.43%	
	PET	0.358	23.43%	
	LLDPE	0.592	38.68%	
Processing	Metallization	0.017	1.10%	13.28%
	Polymer Extrusion	0.186	12.19%	
End of Life	Disposal	0.003	0.17%	0.23%
	Recycling	0.001	0.06%	
	Total	**1.530**		

Raw materials contribute to the most embodied energy at 86.5%. The inner LLDPE layer makes up the most embodied energy at 38.68%, followed by the two PET layers, both at 23.43%. The total embodied energy for the MPET laminate is 1.53 kWh. See Figure 16 and Table 17 for further breakdown of these results.

7.4. Impact Comparison

7.4.1. Total Impact

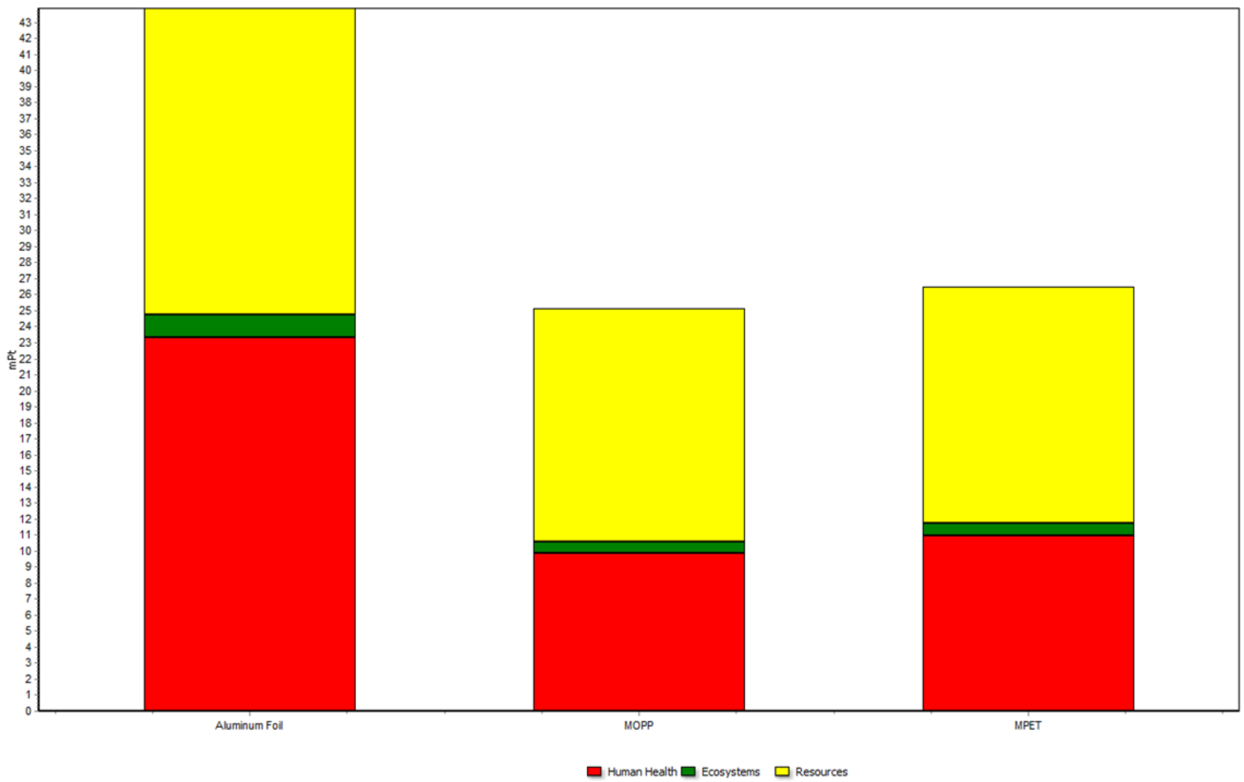


Figure 17 Ecopoint comparison

The results expressed here represent the total impact of each alternative as generated by the ReCiPe Endpoint (H) method. The single score impact is the largest for the aluminum foil laminate. At 43.9 mPt for the foil laminate, 25.2 mPt for the MOPP laminate, and 26.5 mPt for the MPET laminate, the metallized polymers have a total impact equal to 57% and 60% of the foil laminate, respectively (Figure 17).

Out of the three categories, human health, ecosystems, and resources, the aluminum foil laminate generates most damage in the human health category at 23.3 mPt. This is due to the potential health implications associated with aluminum mining and processing. Although aluminum use is minimal in the metallized polymer alternatives, the overall damage on resources is not significantly less than that of the foil laminate. The damage to resources for the MOPP and MPET laminates are 14.6 mPt and 14.7 mPt, respectively. The damage to resources from the foil laminate is 19.1 mPt. Therefore, the damage to resources is only about 23% less for these metallized alternatives than for the aluminum foil laminate. This is due to the extra polymer material required for the barrier layer of the metallized package film. Polymer materials such as the OPP and PET used in these barrier layers require a significant input from fossil-based raw materials for their creation.

7.4.1.1. Characterization

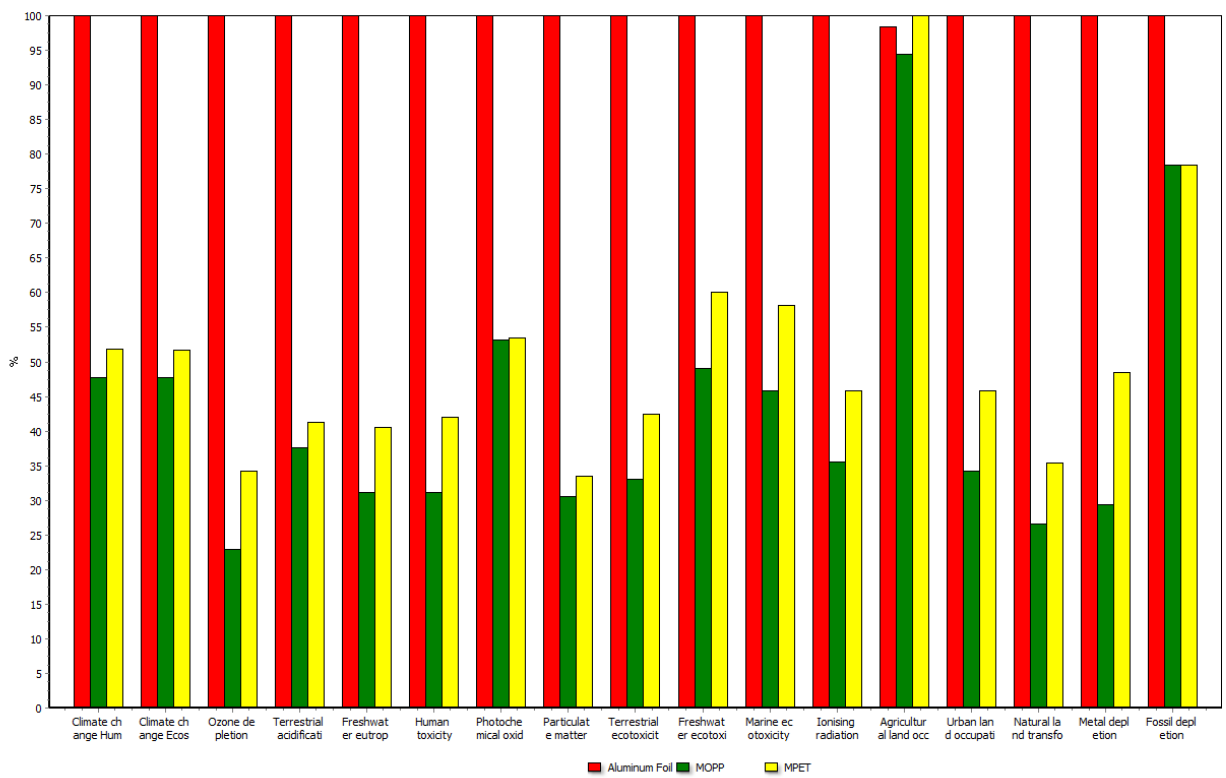


Figure 18 Characterization of impact categories

Seen in Figure 18 is the characterization of impacts across 17 categories from SimaPro and ReCiPe Endpoint (H). This represents the relative contributions of emissions and resource consumption to each appropriate impact category (Baumann & Tillman, 2004). These are the impact categories that are normalized and weighted to produce the results seen in Figure 17. The bar graph shows results in values relative to the largest contributor to each impact category.

The aluminum foil laminate has the highest impact across categories such as climate change, acidification, eutrophication, human toxicity, particulate matter, metal depletion, and fossil depletion (Table 18). It did, however, show less impact in the agricultural land occupation category in which the differences are less than six percent. The MOPP laminate has slightly less impact across all categories, except for fossil depletion in which it and the MPET laminate contribute the same. Both are at a value of 78% of the foil laminate for fossil depletion. This is due in part to the extra polymer material associated with the barrier layer of each. Even though a 50 nm layer of vaporized aluminum requires 97% less energy to produce than a standard layer of foil (Copeland & Astbury, 2010), when the complete packaging laminate is assessed the impact to fossil depletion is significant for metallized polymers. As expected, the metal depletion is less for the metallized polymers, but not insignificant as there are metal depletion impacts associated with the polymers and electricity used to create these materials. This result is significant in that it better represents the true impact on metal depletion rather than simply stating that metallized polymers require 99% less aluminum than a standard foil layer.

Table 18 Impact category values

	Aluminum Foil	MOPP	MPET	
Impact Category	**Value**			**Unit**
Climate Change	5.34E-07	2.54E-07	2.76E-07	DALY
Human Toxicity	8.97E-08	2.79E-08	3.77E-08	DALY
Particulate Matter	1.62E-07	4.96E-08	5.44E-08	DALY
Acidification	8.09E-12	3.04E-12	3.33E-12	species.yr
Eutrophication	5.93E-12	1.84E-12	2.40E-12	species.yr
Metal Depletion	9.44E-04	2.77E-04	4.57E-04	$
Fossil Depletion	2.25E-02	1.76E-02	1.76E-02	$

7.4.2. Global Warming Potential

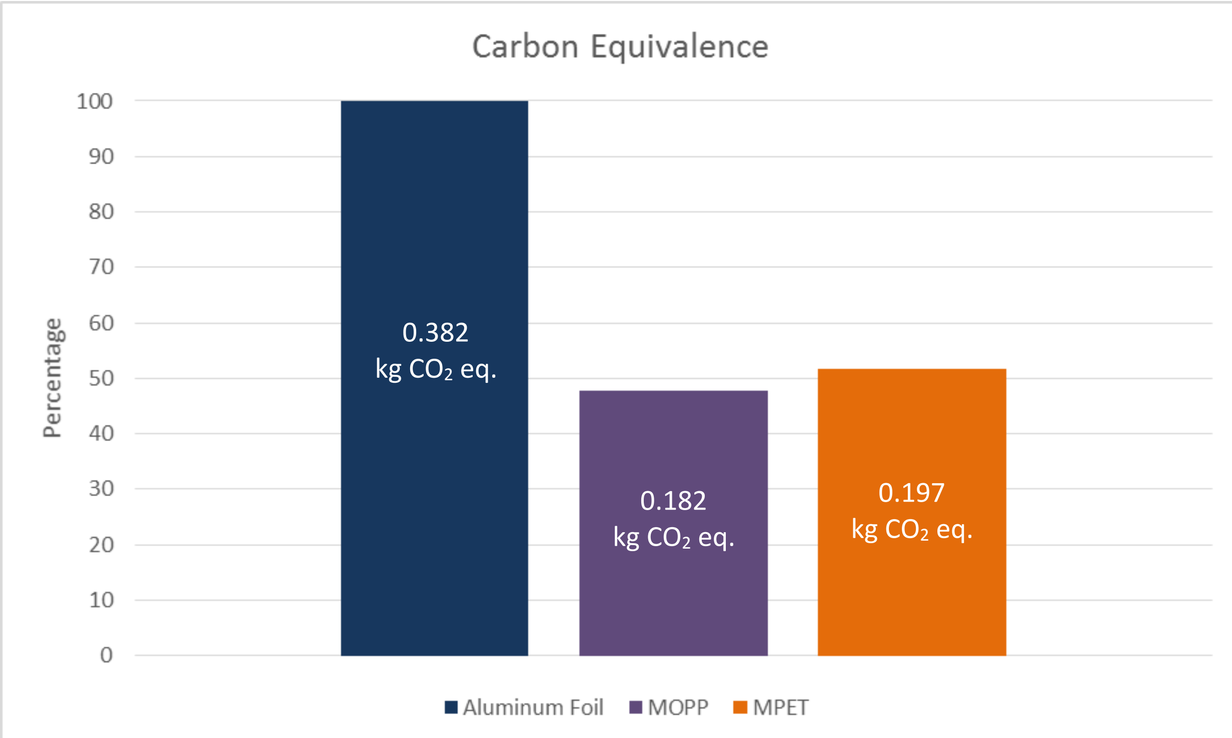


Figure 19 GWP relative comparison

The global warming potentials can be seen in Figure 19 as generated by the IPCC 2007 GWP 100a method. These results are expressed in percentages relative to the most impactful. The overall global warming potential for the MOPP laminate is 48% of the aluminum foil laminate. The MPET laminate is 52% of the foil laminate. The slight difference is GWP between the MOPP and MPET laminates is due to a higher carbon footprint associated with the production and disposal of PET.

7.4.3. Embodied Energy

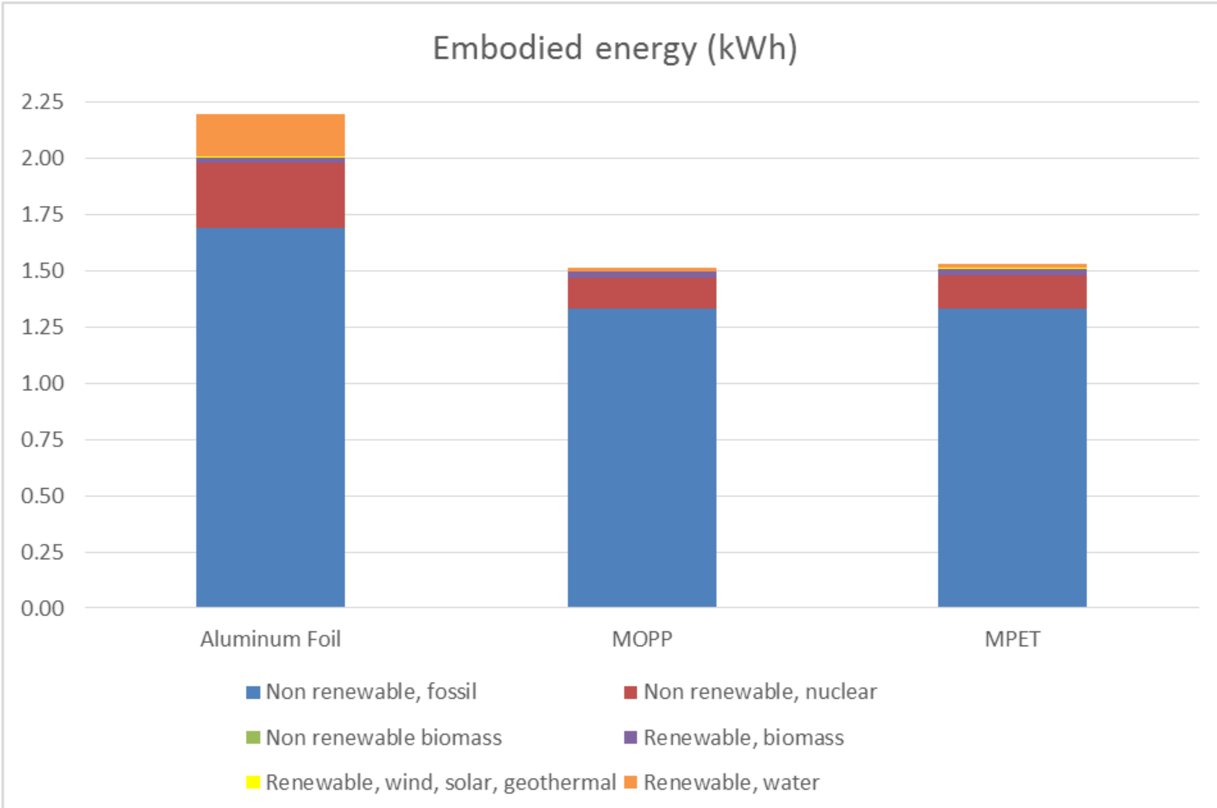


Figure 20 Embodied energy comparison

The embodied energy output produced via the Cumulative Energy Demand method is made up of six energy sources as seen in Figure 20. The total embodied energy values reported are 2.197, 1.512, and 1.530 kWh for the aluminum foil, MOPP, and MPET laminates, respectively. These values include all energy sources, non-renewable and renewable. Perhaps of greater concern is the non-renewable energy use. When only taking non-renewable energy from fossil fuels and nuclear into consideration, the results are 1.98 kWh for aluminum foil, 1.47 kWh for MOPP, and 1.48 kWh for MPET. This equates to a savings of around 25-26% in non-renewable energy with the metallized polymers.

Even with the significant reduction in aluminum material with metallized polymers, the non-renewable energy is still quite high. Embodied energy takes into consideration the energy of the material itself. Many polymers have an energy content of around 40-46 MJ/kg, mostly derived from fossil-based resources, which is factored into the non-renewable embodied energy. This is part of the reason why the metallized alternatives, which have one extra polymer layer than the foil laminate, have a large contribution to this category. Also, the production of aluminum from bauxite ore is energy intense, but a large part of the energy required for this processing comes from hydro power (Franklin Associates, 2014). This offsets some of the reliance on non-renewable fossil energy associated with the aluminum foil laminate.

7.5. Sensitivity Analysis

After compiling all initial results, a basic sensitivity analysis was performed to test the influence of assumptions associated with the original data. From the analysis, it was determined that the electricity consumption and geography-specific grid mixes had little effect on the outcome of the results. Altering the end of life waste scenario did have a more significant effect on results, but the overall trend still showed that the MOPP and MPET laminates are less environmentally impactful.

7.5.1. Electricity Consumption

For this scenario, the electricity consumption associated with the barrier layer manufacturing was altered for all three alternatives at one time. In an attempt to bring the results closer together, the

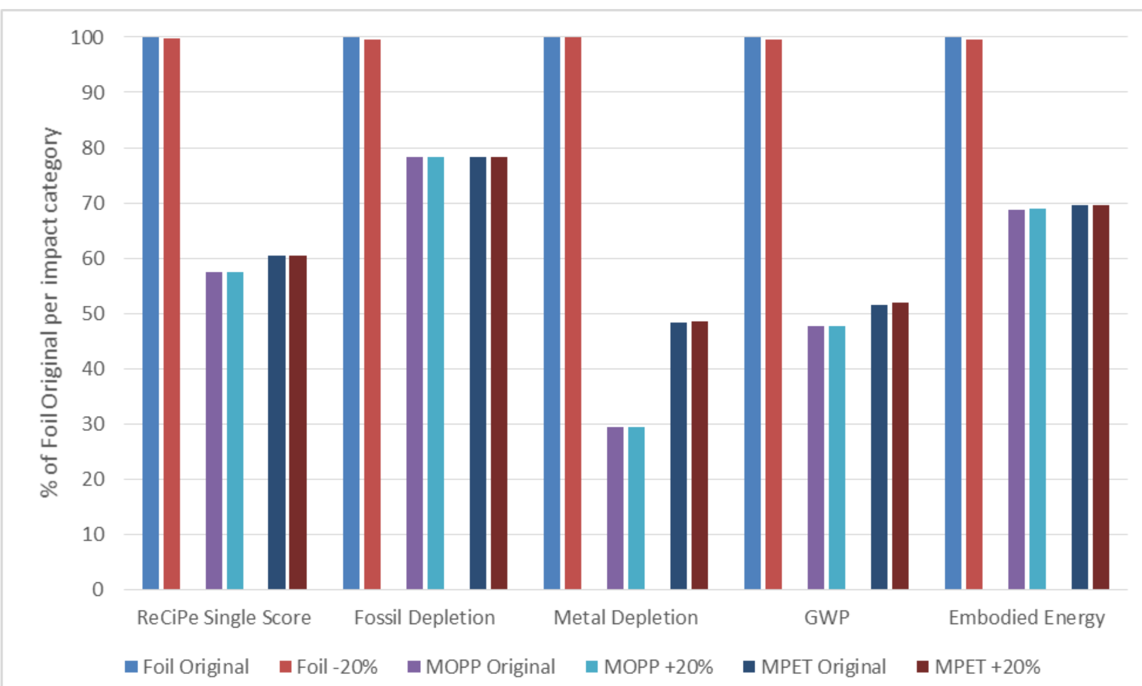


Figure 21 Electricity consumption sensitivity

electricity associated with the process of rolling aluminum foil was decreased by 20%. The electricity associated with the process of metallizing a polymer web was increased by 20%. This resulted in no more than half a percent change between the original and altered scenarios with the foil laminate showing slight decreases and the MOPP and MPET showing slight increases (Figure 21). Of the necessary manufacturing steps for creating a metallized barrier layer, the film extrusion process for producing the polymer web is more impactful than the metallization process. More significant savings can be seen if electricity consumption control is realized in the polymer web extrusion process.

7.5.2. US vs. European Grid Mix

An average European grid mix was used in the original model of the metallization process. To determine the sensitivity of this assumption, the electricity mix was altered to represent that of an average United States grid mix. This change increased the global warming potential and total impact (ecopoints) by half a percent or less for the MOPP and MPET laminates. The embodied energy was not altered in doing this. The fossil-based energy supply for electricity production in the US grid mix is slightly higher than that of the European mix which is why this slight increase was witnessed.

7.5.3. End of Life Waste Scenario

The original model of all three packaging alternatives used a ratio of 80% directed to landfill and 20% directed to incineration at the end of life. This ratio represents a typical outcome for municipal solid waste in the United States after recovery and recycling. A ratio of 50% to landfill and 50% to incineration was also modeled to assess a more typical outcome in Europe. Per the system boundary, neither one of these is specified to generate credits back to the packaging alternatives for this analysis, but the potential credits for waste-to-energy (W-T-E) disposal are explored and discussed later.

Since no credits in terms of energy creation or carbon offset are factored in to the model, the impacts increased slightly for the 50/50 ratio waste scenario. The total impact, in ecopoints, increased by 1.3% for the aluminum laminate, 2.9% for the MOPP laminate, and 3.5% for the MPET laminate. Interestingly, the associated energy of each alternative did not increase compared to the original 80/20 waste scenarios. The energy demand associated with the additional 30% incineration is heavily outweighed by the energy content of the materials themselves, as well as the process energy used to create these materials.

The global warming potential of each alternative increased due to the increased ratio of carbon material being incinerated. The aluminum foil laminate experienced a 3.5% increase, the MOPP laminate a 9.4% increase, and the MPET laminate increased the most at just under 11%, all compared to the original 80/20 waste scenarios. The metallized alternatives experienced greater increases in GWP due to the larger quantity of polymer material compared to the aluminum foil laminate. The resulting GWP for the MOPP laminate increased from 48% of the GWP of the aluminum foil laminate to 50%. The GWP for the MPET laminate increased from 52% of the GWP of the aluminum foil laminate to 55%. Even so, the metallized polymer laminates remain less impactful to the environment than the foil laminate.

Overall, the impacts associated with an increased incineration waste scenario are greater when no credits are taken into consideration. As previously stated, polymers have high energy content that, if captured and used to produce energy during incineration, can offset required energy inputs from fossil materials such as coal, oil, natural gas, etc. used to produce electricity. Thus, the carbon emissions associated with these fossil materials can be offset as well. These potential offsets are discussed further.

7.5.3.1. Energy and Carbon Offsets from W-T-E

By not taking any energy or carbon offset credits into account, the total impact and GWP of the metallized polymer laminates increased more than the aluminum foil laminate when end of life reflected the higher incineration rate. This is due to the greater amount of polymer material in the metallized alternatives, but because of this material, there is a greater possibility for energy and carbon offsets at the end of life (See section 12.8.3 for calculations).

To calculate the potential energy and carbon offsets associated with each alternative, a heating value of 46 MJ/kg was used for both polypropylene and polyethylene, and 25 MJ/kg was used for polyethylene terephthalate (Andrady & Neal, 2009; Themelis et al., 2011). Literature shows that during incineration, with adequate temperature and oxygen levels, aluminum oxidizes and releases energy due to this oxidation (Lopez, Roman, Garcia-Diaz, & Alguacil, 2015; EAA, 2014). However, this area of study is still not well developed, and the net recoverable energy is dependent on many variables. Lopez et al. (2015) states that, under laboratory test conditions, flexible packaging with low aluminum content (~6 μm thick) showed a calorific gain of around 13.5 MJ/kg. Only 17% of the aluminum actually oxidizes to produce this energy though (Lopez et al., 2015). For the three packaging laminates in this study, an efficiency of 17.8% was used for the waste to electrical energy incineration process as an average for a mixed MSW plant (US EPA, 2015). Considering the variability in energy from aluminum incineration and the relatively low output, it is ignored for this analysis.

Complete combustion of polymer material was assumed, e.g., for the 80/20 scenario, 20% of the mass of each polymer in each packaging laminate was converted to electrical energy. Due to its higher energy content, the MOPP laminate has the largest recoverable energy through incineration, followed by the MPET laminate, and then the aluminum foil laminate. The energy these materials release could be used to replace electrical energy created from fossil fuels. Using a value of 0.191 kg CO_2 eq. per 1 MJ of electricity produced to represent an average US grid footprint (IPCC, 2007) gives the potential offsets from producing this electricity from the incineration of the packaging materials instead (Table 19). If these credits were allocated back to the packaging alternatives, the MOPP laminate would offer the greatest carbon offset potential, and actually results in lower GWP for the waste scenario with a larger incineration ratio. The MPET laminate has the largest quantity of PET material which has a relatively high GWP compared to its energy content (heating value). Therefore, the MPET laminate does not fare as well when the incineration rate is increased. The aluminum foil laminate has the least potential for energy recovery and carbon offsets of all, but still shows reduced carbon emissions with an increase in incineration. When considering the potential recovery of energy and

Table 19 Carbon emissions per waste scenario

		Aluminum Foil	MOPP	MPET
80/20	Total	0.382	0.182	0.197
	Potential offset	-0.012	-0.017	-0.015
50/50	Total	0.395	0.199	0.219
	Potential offset	-0.029	-0.042	-0.036

offsetting of carbon, even if these offsets are credited to another product, the analysis affirms that the MOPP laminate fares the best, followed closely by the MPET laminate.

7.6. Additional Considerations

Previously mentioned, but not yet discussed, were the impacts of the evaporation boats, benefits associated with recycling the vaporized aluminum overspray, changing material thickness or number of layers of the alternatives, and use of recycled material content within the packaging alternatives.

7.6.1. Evaporation Boats

Considering that the inventory created to represent the evaporation boats was not exhaustive, and the boat material 'consumed' per square meter of metallized film is so small, the associated impacts were negligible. An extensive study and development of a more accurate life cycle inventory of these materials would allow for greater accuracy of their contribution to the metallization system.

7.6.2. Aluminum Overspray Recycling

As mentioned, this analysis does not directly allocate any credits from recycling the aluminum overspray from the metallization process back to the MOPP nor MPET laminates. The potential credits have been calculated per the functional unit of this system (square meter of film) and are displayed in Table 20 for reference. These values are calculated based on the 50% overspray associated with depositing a 50 nm layer of vaporized aluminum onto the polymer sheets during the metallization process. It is assumed that the entirety of the overspray is cleaned from the machine post-metallization and recycled. These credits are generated assuming that the aluminum material would be re-processed to a usable form, replacing the need for virgin aluminum manufacturing, thus off-setting some of its associated impacts. These results were generated via IPCC 2007 GWP 100 (carbon credit), Cumulative Energy Demand (energy credit), and ReCiPe Endpoint H (total impact credit).

Table 20 Potential aluminum recycling credits

Carbon credit	-0.00147 kg CO_2 eq.
Energy credit	-0.023 MJ
Total impact credit	-0.00015 ecopoint

7.6.3. Altering Thicknesses and Layering

Decreasing the thickness of any one layer of these packaging alternatives would reduce the environmental impacts associated with it, since the raw materials contribute to the largest portion of impacts across the board. This, however, is not considered for any of the layers of any laminate. Each layer is already either near or at its lowest functional thickness. Standard PET thickness is 12 μm, LDPE can range from 25 μm to 100 μm, and standard OPP thickness can range from 15 μm to 50 μm (Dixon, 2011). The thicknesses of polymer materials in this study all fall at the lower end of these ranges at 12 μm for PET, 30 μm for LLDPE, and 18 μm for OPP. Reducing the thickness of the LLDPE layer of each alternative would be the most effective if possible, but is not considered.

Altering the thicknesses of aluminum foil and vaporized aluminum are also not reasonable. The aluminum foil layer in this study is 7 μm thick which falls at the low end of standard foil with 6 μm being a typical extreme due to processing capabilities and the resulting functional properties (Dixon, 2011). Even so, a quick analysis within SimaPro showed that the aluminum foil layer would need to be at least half as thick (3.5 μm) to reduce the laminate's impacts to within range of the metallized polymer alternatives. The renewable energy demand and fossil depletion become equal for each alternative under this scenario, but even then the global warming potential for the aluminum foil laminate is still around 25-30% more than MOPP and MPET laminates. As for the MOPP and MPET laminates, reducing the layer of vaporized aluminum would show negligible results in that it already only contributes to a small percentage of the impacts.

One other scenario that could potentially reduce environmental impacts is the removal of one of the polymer layers from the alternatives. For this particular study, this was not considered due to the fact that the outer PET layer is necessary for the reverse image graphics that are seen on all snack packaging like this. The center metallized polymer layer of the MOPP and MPET laminates is necessary for barrier properties, and the inner LLDPE layer is necessary for heat sealing the package once filled with food product. In theory, it is possible to remove the outer PET layer of the MOPP and MPET laminates and still have a functional package, but this eliminates the ability to provide graphics, which are essential.

7.6.4. Recycled Material Content

Although it is feasible to use recycled content in polymer film layers, this scenario is not assessed under the assumption that degraded functional properties of the recycled content is unacceptable for these packaging films. Recycled aluminum is also not considered in this study because it is not often used for the production of foil. As stated before, any foil under the thickness of 17 μm will likely have pinholes. This is even more true for the case of recycled aluminum (Marsh & Bugusu, 2007).

7.7. Use Phase Results

The use phase for this study was comprised of two things: "scrap material" associated with different size laminate packages and reduction in barrier layer properties due to theoretical shipping and handling via flex testing. The "scrap material" is defined as the inner barrier layer material where the package is heat sealed shut. For instance, for the aluminum foil laminate, the aluminum foil layer is considered scrap material in the heat sealed area. Within this area, it is providing little barrier protection for the food and is not aiding in the heat seal capabilities; it is essentially scrap material.

7.7.1. Consumer Choice

Two scenarios were defined as a means to offer insight to the consumer of these products in making more environmentally-friendly choices. The first packaging scenario is defined as "family sized" package and the second is the "individual sized" package. The family size bags are larger and have a minimum of 10 one ounce servings for the sake of this study. The individual size bags contain around three

Table 21 Material consumed per serving

	Avg area per bag (m^2)	Avg % of sealed area	Avg # of servings per bag	Bag area per serving (m^2)	Sealed area per serving (m^2)
Family Sized	0.222	7.96	13.5	0.0164	0.0013

	Avg area per bag (m^2)	Avg % of sealed area	Avg # of servings per bag	Bag area per serving (m^2)	Sealed area per serving (m^2)
Individual Sized	0.072	8.5	2.125	0.0339	0.0029

servings or fewer and are smaller in size to accommodate just one consumer. With the few samples from each category measured for overall dimension, it was determined that the heat sealed areas of each type were around 8% of the total area. This means that, in theory, 8% of either aluminum foil, MOPP, or MPET barrier layers are not providing barrier to the food product for every sealed package. The difference is that there are more servings in the family size bag than the individual size. Therefore, on a per serving basis, about half as much material is consumed with the family size bag than the individual size (Table 21). The choice between different size bags is a role that the consumer plays in these packaging alternatives' life cycles, and by purchasing "family sized" potato chip bags, less packaging material is consumed per serving of potato chips.

7.7.2. Flex Testing Results

The flex testing was conducted to simulate possible influence on barrier properties from shipping and handling of the laminates. The OTR of the samples were measured under environmental test conditions of 73°F and 0% relative humidity. The results showed that the aluminum foil laminate had the lowest (best) OTR before and after flexing and the MOPP had the highest (worst). This shows that even during shipping and handling, the aluminum foil laminate maintains a high level of barrier capabilities. Even though the MOPP had the highest OTR before and after flexing, it was affected the least out of all the alternatives (Table 22). These results also show that all of the laminates maintain their high barrier performance capabilities and justify basing the functional unit around this definition.

Table 22 OTR flex test ($cm^3/m^2/day$)

	Before Flexing	After Flexing
PET/AluFoil/LLDPE	0.024	0.093
PET/MOPP/LLDPE	2.522	5.462
PET/MPET/LLDPE	0.234	2.534

8. Conclusions and Recommendations

An environmental study of three packaging laminates (foil centered laminate PET/AluFoil/LLDPE, metallized polypropylene centered laminate PET/MOPP/LLDPE, and metallized polyethylene terephthalate centered laminate PET/MPET/LLDPE) was conducted to determine the environmental burdens of metallized film laminates compared to an aluminum foil laminate across the raw material, manufacturing, and end of life phases. Impacts were generated using ReCiPe Endpoint H, IPCC 2007 GWP 100, and Cumulative Energy Demand assessment methodologies available within SimaPro.

The impact assessments showed that the metallized polymer laminates had lesser impact than the aluminum foil laminate, as expected. Rather than only investigating the aluminum reduction and energy savings of vaporized aluminum compared to aluminum foil, this study more accurately represents a life cycle comparison of metallized polymer laminates to that of aluminum foil laminates. A previous study suggested a 97% reduction in energy for creating a 50 nm layer of vaporized aluminum compared to aluminum foil (Copeland & Astbury, 2010). Although this is true, and was verified in this study, that figure is misleading as to the energy requirements for a complete flexible packaging system.

The total impact (ecopoints) of the MOPP and MPET laminates were 57% and 60% that of the aluminum foil laminate across the raw material, processing, and end of life phases, respectively. Both metallized laminates offered around 50% of the global warming potential of the aluminum foil laminate. However, these only offered a savings of around 25-26% in non-renewable embodied energy due to greater polymer content. The MOPP and MPET laminates offered the same impact to fossil depletion at \$1.76E-02 compared to \$2.25E-02 for the aluminum foil laminate. The MOPP, at \$2.77E-04, had less of an impact on metal depletion than both the MPET laminate at \$4.57E-04 and the aluminum foil laminate at \$9.44E-04.

This study shows that total film thickness is not as important as the material composition of the laminated structure. The aluminum foil laminate was the thinnest, but had the greatest impact; the MOPP laminate was the thickest, but had the least impact. Unless a near-perfect barrier is required for a certain packaging condition, metallized film centered laminates are the more environmentally friendly choice in high barrier applications as considered here.

9. Future Work

The work presented here has potential for future improvements. Ecoinvent version 2.2 was the primary database used to conduct this study. SimaPro has since updated its databases to reference ecoinvent version 3. Re-assessing the model using ecoinvent version 3 may lead to more accurate/up-to-date results. Improving the detail and accuracy of the metallization life cycle inventory data would also increase the accuracy of results. First-hand access to very detailed data of the metallization process and evaporation boat life cycle was not attainable for this study, but could increase the overall accuracy. The results show that the impacts due to the aluminum and polymer raw materials outweigh the impacts of the manufacturing processes used to convert them to packaging though, so this may not lend significantly more accurate results. Further research into the end of life of these materials could broaden the understanding of their impacts. A better understanding of how aluminum oxidizes during incineration could change the end of life impacts of the aluminum foil laminate. Although 'recycling' is not currently a viable option for these materials, it may be in the future. An analysis of recycling via pyrolysis as an end of life for these laminates may be necessary to expand the understanding of future methods of disposal.

10. LCA Software and Database Limitations

One of the current downfalls of environmental studies/life cycle assessments is the inability to easily compare results. There are many factors, even beyond the establishment of a functional unit and assumptions made by the analyst, which can hinder the representation of a product or system. Sensitivity and uncertainty analyses help to reduce this, but this topic area is still worth noting. The environmental software used to conduct the study, the LCI databases, and even the method by which the impact results are calculated all have an effect and can limit the ability to compare these results to those from other software, databases, and methods.

This environmental assessment was conducted in SimaPro version 8, and the life cycle inventory data primarily comes from the ecoinvent version 2.2 database. The results were produced via ReCiPe Endpoint (H), IPCC 2007 GWP 100, and Cumulative Energy Demand. Using a different software, databases, and impact methods would lead to slightly different results for the same inputs.

11. References

Aluminum. (2014). Retrieved from http://www.madehow.com/Volume-5/Aluminum.html

Aluminum Association. (2008). Rolling aluminum: From the mine through the mill. Retrieved from http://www.aluminum.org/sites/default/files/ Rolling_Aluminum_From_The_Mine_Through_The_Mill.pdf

Aluminum Foil. (1997). In A. L. Brody & K. S. Marsh (Eds.), The Wiley Encyclopedia of Packaging Technology (2nd ed.). New York, NY: Wiley-Interscience.

Andrady, A. L., & Neal, M. A. (2009). Applications and societal benefits of plastics. *Philosophical Transactions of the Royal Society* (Vol. 364, pp. 1977-1984).

ASTM International. Standard Practice for Conditioning Flexible Barrier Materials for Flex Durability (Vol. F392/F392M - 11).

Barlow, B. (2015). [Email Communication]

Barlow, C. Y., & Morgan, D. C. (2013). Polymer film packaging for food: An environmental assessment. 78, 74–80. doi: 10.1016/j.resconrec.2013.07.003

Baumann, H., & Tillman, A.-M. (2004). *The Hitch Hiker's Guide to LCA: An orientation in life cycle assessment methodology and application*. Lund, Sweden: Studentlitteratur AB.

Bishop, C. A. (2007). *Energy and Environmental Issues of Roll-to-Roll Vacuum Deposition*. Paper presented at the SVC 50th Annual Technical Conference Proceedings.

Bishop, C. A. (2015). [Email Communication].

Bishop, C. A., & Mount III, E. M. (2010). Vacuum metallizing for flexible packaging. *Multi-layer flexible packaging technology and applications for the food, personal care and over-the-counter pharmaceutical industries*. Ch. 14, 185-202.

Bobst Manchester Ltd. (2015). [Email communication].

BSRIA. (2012). Life Cycle Assessment - an introduction.

Busser, S., & Jungbluth, N. (2009). The role of flexible packaging in the life cycle of coffee and butter - Springer. *The International Journal of Life Cycle Assessment*, 14(1), 80-91. doi: 10.1007/s11367-008-0056-2

Chatterjee, D. (2006). Developments in Metallised Films for Packaging. United Kingdom: Pira International Ltd.

Copeland, N. J., & Astbury, R. A. (2010). *Evaporated aluminum on polyester: optical, electrical, and barrier properties as a function of thickness and time (Part I).* Paper presented at the 2010 AIMCAL Technical Conference.

Decker, W., Roy, D., Voght, C., Roy, C., & Dabbert, P. (2004). *Metallized Polymer Films as Replacement for Aluminum Foil in Packaging Applications*. Paper presented at the SVC 47th Annual Technical Conference, Dallas, TX.

Delft University of Technology. (2001). Idemat. Retrieved from http://www.idemat.nl/

Dixon, J. (2011). *Multi-layer Packaging for Food and Beverages*. Retrieved from http://www.ilsi.org/Europe/Publications/ILSI-11-011%209%20pack%2003.pdf

EAA. (2014). More aluminum packaging recovered from incinerator bottom ashes than expected! Retrieved from http://www.alufoil.org/tl_files/sustainability/FACT_%20SHEET-Alu_recovery_bottom_ashes_FEB14.pdf

ecoinvent. (2010). ecoinvent Version 2. Retrieved from http://www.ecoinvent.org/database/ecoinvent-version-2/ecoinvent-version-2.html

Edge Environment. What are Ecopoints? Retrieved from http://edgeenvironment.com.au/docs/Australian%20Ecopoints.pdf

Emblem, A., & Emblem, H. (2012). Aluminum foil packaging. *Packaging Technology - Fundamentals, Materials, and Processes* (pp. 163-177): Woodhead Publishing Limited.

Eurostat. (2012). Development of waste treatment in the EU-28, 2004–12 (million tonnes). Retrieved from http://ec.europa.eu/eurostat/statistics-explained/index.php/File:Development_of_waste_treatment_in_the_EU-28,_2004%E2%80%9312_(million_tonnes)_YB15.png

FFPC. (2011). Oxygen Transmission Rate. Retrieved from http://www.flairpackaging.com/pages/packaging_for_dairy_and_deli_flair-flexible_packag/resources/packaging101_meat/Oxygen%20Transmission%20Rate%20%28OTR%29/2

Fowle, J. (2005). Developments in Barrier Films for Packaging (pp. 53). United Kingdom: Pira International.

Frank, W. B., Haupin, W. E., Vogt, H., Bruno, M., Thonstad, J., Dawless, R. K., Kvande, H., & Taiwo, O. A. (2009). Aluminum. *Ullmann's Encyclopedia of Industrial Chemistry*.

Franklin Associates. (2014). Impact of Plastics Packaging on Life Cycle Energy Consumption & Greenhouse Gas Emissions in the United States and Canada. Retrieved from http://plastics.americanchemistry.com/Education-Resources/Publications/Impact-of-Plastics-Packaging.pdf

Granta Design Ltd. (2014). CES EduPack 2014. Retrieved from http://www.grantadesign.com/education/edupack/edupack2014.htm

IPCC. (2007). IPCC Fourth Assessment Report: Climate Change 2007. Retrieved from http://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml

International Organization for Standardization (ISO) (2006). *Environmental management – Life cycle assessment – Principles and framework ISO 14040*.

International Organization for Standardization (ISO) (2006). *Environmental management – Life cycle assessment – Requirements and guidelines ISO 14044*.

Kang, D., Sgriccia, N., Selke, S., & Auras, R. (2013). Comparison of bacon packaging on a life cycle basis: a case study. *Journal of Cleaner Production*, 54, 142-149.

Katz, S. (2013). Flexible Packaging. Retrieved from http://www.labelandnarrowweb.com/issues/2013-04/view_features/flexible-packaging-844652/

Kliaugaite, D., & Staniskis, J. K. (2013). Comparative Life Cycle Assessment of High Barrier Polymer Packaging for Selecting Resource Efficient and Environmentally Low-Impact Materials. *International Journal of Environmental, Earth Science and Engineering*, 7(11), 721-729.

Lopez, F. A., Roman, C. P., Garcia-Diaz, I., & Alguacil, F. J. (2015). Oxidation and waste to energy output of aluminium waste packaging during incineration: A laboratory study. *Waste Management*.

Luhrs, M., Griffing, E., Realff, M., & Overcash, M. (2010). *Life Cycle Inventory Gate-to-Gate of Metallized Biaxially-Oriented Polypropylene*. Paper presented at the AIMCAL Fall Technical Conference.

Marsh, K., & Bugusu, B. (2007). Food Packaging-Roles, Materials, and Environmental Issues. *Journal of Food Science*, 72(3), 39-55.

Mueller, K., Schoenweitz, C., & Langowski, H. C. (2011). Thin Laminate Films for Barrier Packaging Application - Influence of Down Gauging and Substrate Surface Properties on the Permeation Properties. *Packaging Technology and Science*, 25, 137-148. doi: 10.1002/pts.966

Petrie, E. M. (2006). Developments in Barrier Coatings for Plastic Packaging (pp. 21). United Kingdom: Pira International Ltd.

PolyPrint Inc. (2008). Oxygen Transmission Rate. Retrieved from http://www.polyprint.com/flexographic-otr.htm

Siracusa, V., Dalla Rosa, M., Romani, S., Rocculi, P., & Tylewicz, U. (2011). Life Cycle Assessment of multi-layer polymer film used on food packaging field. 1, 235–239. doi: 10.1016/j.profoo.2011.09.037

Siracusa, V., Ingrao, C., Lo Giudice, A., Mbohwa, C., & Dalla Rosa, M. (2014). Environmental assessment of a multi-layer polymer bag for food packaging and preservation: An LCA approach. 62, 151–161. doi: 10.1016/j.foodres.2014.02.010

Smithers Pira. (2013). Global Flexible Packaging Industry to Reach $231 Billion by 2018. Retrieved from https://www.smitherspira.com/market-reports/global-flexible-packaging-industry-to-reach-231-billion-by-2018.aspx

SMPC. (2009). Impact on Barrier of Pinholes in Foil Layer of a Lamination. Retrieved from http://faqs.sterilizationpackaging.org/questions/7

Struller, C. F., Kelly, P. J., Copeland, N. J., & Liauw, C. M. (2012). Aluminum oxide barrier layers on polymer web.

Themelis, N. J., Castaldi, M. J., Bhatti, J., & Arsova, L. (2011). *Energy and economic value of non-recycled plastics and municipal solid wastes that are currently landfilled in the fifty states*. Retrieved from http://www.seas.columbia.edu/earth/wtert/sofos/ACC_Final_Report_August23_2011.pdf

US EPA. (2014). Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2012. Retrieved from http://www.epa.gov/solidwaste/nonhaz/municipal/pubs/2012_msw_fs.pdf

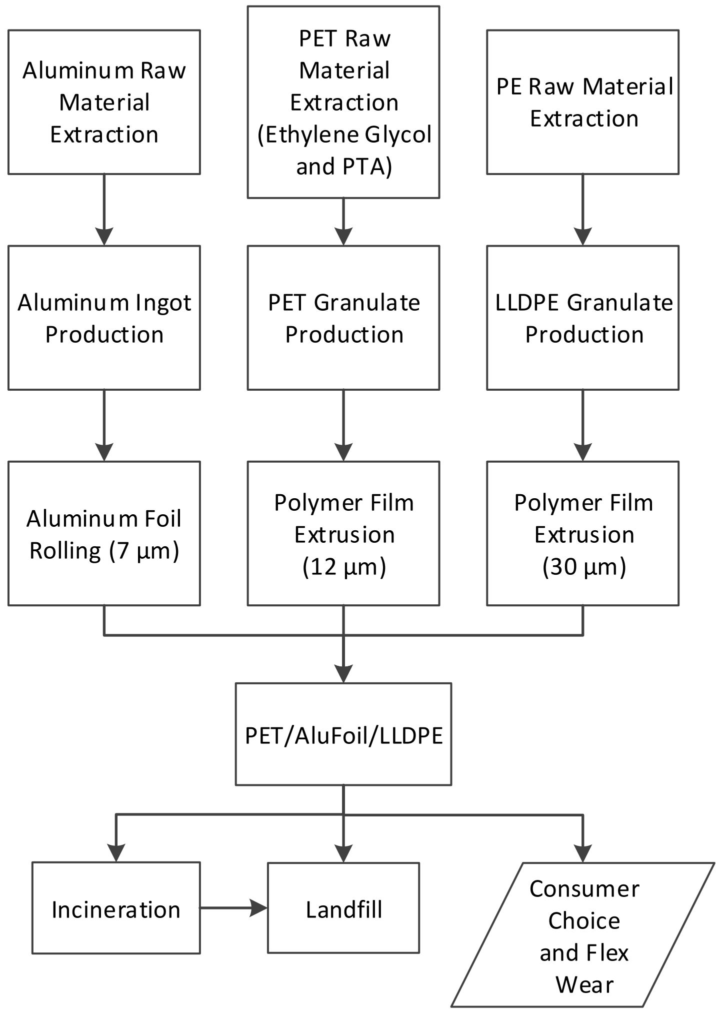
US EPA. (2015). WARM Version 13 - Combustion. Retrieved from http://www3.epa.gov/climatechange/wycd/waste/downloads/combustion-chapter10-28-10.pdf

Vidal, R., Martinez, P., Mulet, E., Gonzalez, R., Lopez-Mesa, B., Fowler, P., & Fang, J. M. (2007). Environmental assessment of biodegradable multi-layer film derived from carbohydrate polymers. *Journal of Polymers and the Environment*, 15(3), 159-168. doi: 10.1007/s10924-007-0056-5

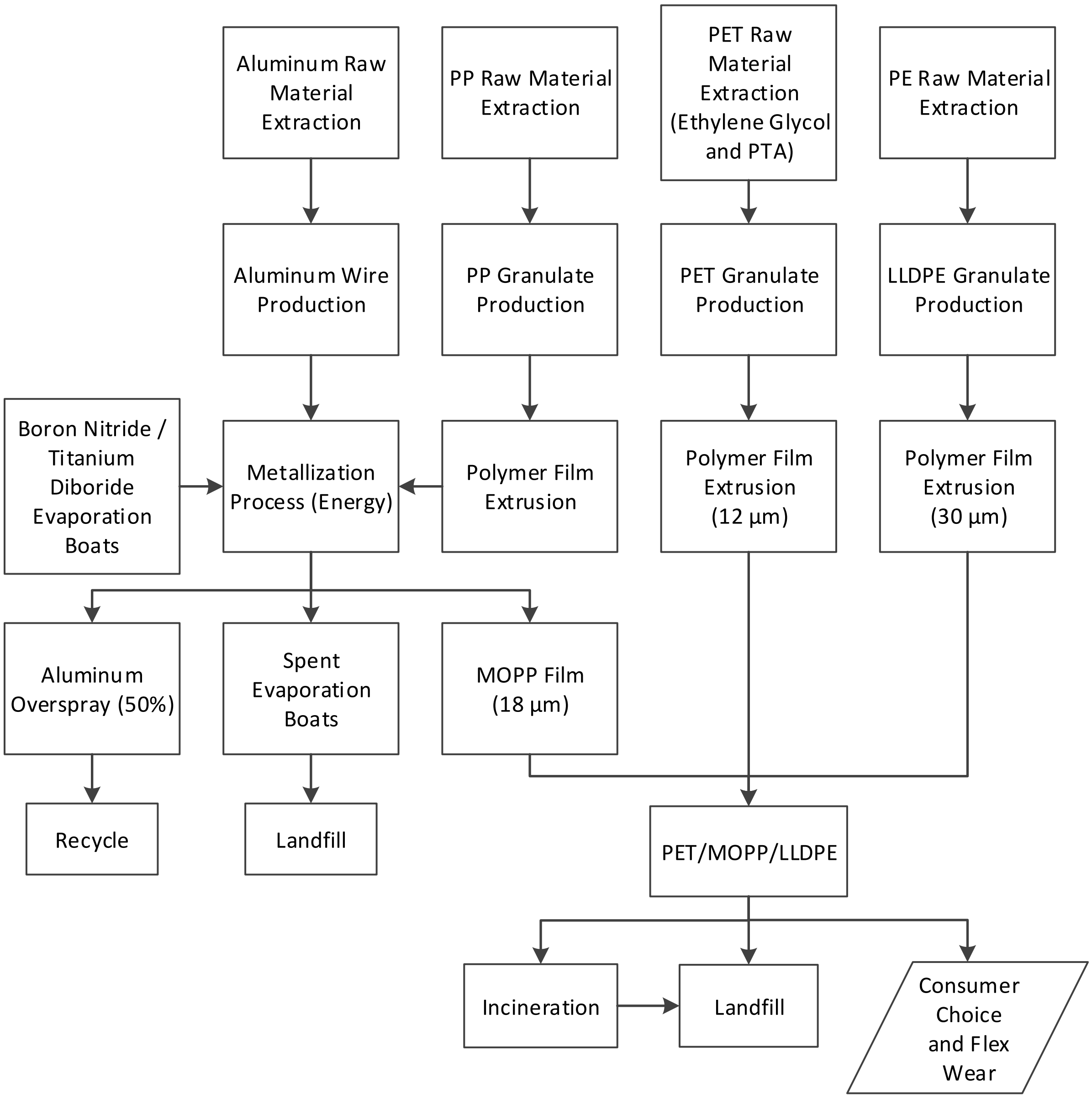
Xie, M., Li, L., Qiao, Q., Sun, Q., & Sun, T. (2011). A comparative study on milk packaging using life cycle assessment: from PA-PE-Al laminate and polyethylene in China. 19, 17–18, 2100–2106. doi: 10.1016/j.jclepro.2011.06.022

12. Appendix

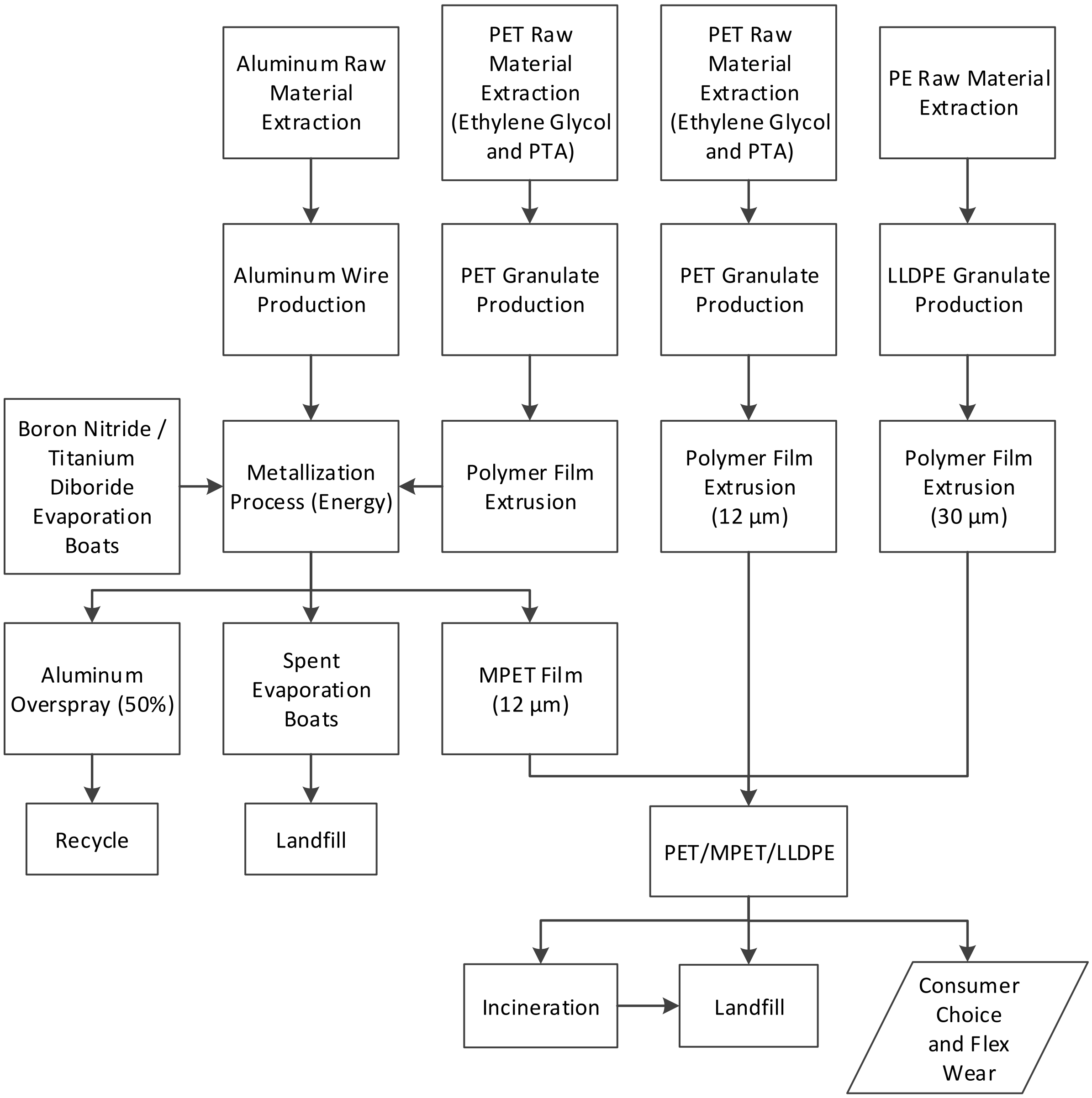
12.1. PET/AluFoil/LLDPE System Flow Diagram



12.2. PET/MOPP/LLDPE System Flow Diagram



12.3. PET/MPET/LLDPE System Flow Diagram



12.4. SimaPro Impact Assessment Methods

The following are descriptions of the methods chosen in SimaPro to analyze the potential impacts associated with each of the packaging alternatives. In italics are the actual method names as they appear within SimaPro.

12.4.1. Total Impact

ReCiPe Endpoint (H) V 1.07, World ReCiPe H/A

The default ReCiPe endpoint method is the Hierarchist version. World ReCiPe H/A refers to normalization values of the world with average weighting criteria. This version of ReCiPe is from the year 2012 and the results are expressed in ecopoints.

12.4.2. Global Warming Potential

IPCC 2007 GWP 100a V 1.02

This method contains the climate change factors of the Intergovernmental Panel on Climate Change for a 100 year timespan. The 100 year timespan is most commonly used in assessments such as this. This method was last updated in 2009 and expresses results as kg CO_2 equivalent. If necessary, the results from this section can be converted to lbs CO_2 equivalent with this relationship 1 kg = 2.205 lbs.

12.4.3. Embodied Energy

Cumulative Energy Demand V 1.08

This method calculates the total energy associated with the life cycle of a system and expresses the results in MJ. This method takes into consideration 6 different energy sources: non-renewable from fossil, nuclear, and biomass, and renewable from biomass, wind, solar, and geothermal, and water. Results were converted to kWh using the relationship 1 kWh = 3.6 MJ.

12.5. PET/AluFoil/LLDPE Model Notes

The raw materials, processing, and end of life descriptions for the aluminum foil laminate are recorded in the following section. In italics are the actual processes from the SimaPro inventory that were used to best represent each phase. *Rolling of aluminum foil I* is the only process that was not taken from the ecoinvent database for this particular model.

12.5.1. Raw Materials

Aluminum Foil

Aluminum, primary, at plant/RER U

Represents the production of virgin aluminum ingot.

PET outer layer

Polyethylene terephthalate, granulate, amorphous, at plant/RER U

Represents average data for the production of virgin PET from ethylene glycol and PTA.

LLDPE inner layer

Polyethylene, LLDPE, granulate, at plant/RER U

Represents aggregated data for the production of virgin LLDPE.

12.5.2. Processing

Aluminum foil rolling

Rolling aluminium foil I

Represents the life cycle data for rolling of aluminum foil of thickness ranging from 7-12 μm. For one kg of foil, and input of 1.015 kg of aluminum ingot is specified.

PET film extrusion

Extrusion, plastic film/RER U

Represents the film conversion process and is noted that for one kg of input material results in 0.976 kg of extruded film.

LLDPE film extrusion

Extrusion, plastic film/RER U

Represents the film conversion process and is noted that for one kg of input material results in 0.976 kg of extruded film.

12.5.3. End of Life

Landfill scenario – this represents the ratio of materials within the aluminum foil laminate that could be destined for the landfill. This landfill scenario was then specified at 80%, which associates 80% of each material to the landfill and specifies the impacts based on the quantity of each material.

Disposal, aluminium, 0% water, to sanitary landfill/CH U

Aluminum foil mass is 19.184 g, or 29.87%

Disposal, polyethylene terephthalate, 0.2% water, to sanitary landfill/CH U

PET mass is 16.475 g, or 25.66%

Disposal, polyethylene, 0.4% water, to sanitary landfill/CH U

LLDPE mass is 28.555 g, or 44.47%

Incineration scenario - this represents the ratio of materials within the aluminum foil laminate that could be destined for incineration. This incineration scenario was then specified at 20%, which associates 20% of each material to incineration and specifies the impacts based on the quantity of each material.

Disposal, aluminium, 0% water, to municipal incineration/CH U

Aluminum foil mass is 19.184 g, or 29.87%

Disposal, polyethylene terephthalate, 0.2% water, to municipal incineration/CH U

PET mass is 16.475 g, or 25.66%

Disposal, polyethylene, 0.4% water, to municipal incineration/CH U

LLDPE mass is 28.555 g, or 44.47%

12.6. PET/MOPP/LLDPE Model Notes

The raw materials, processing, and end of life descriptions for the MOPP laminate are recorded in the following section. In italics are the actual processes from the SimaPro inventory that were used to best represent each phase. All processes were taken from the ecoinvent database for this particular model.

12.6.1. Raw Materials

Metallized OPP

Aluminium, primary, at plant/RER U

Accounts for the aluminum deposited onto the polypropylene sheet as well as the 50% overspray associated with the metallization process

Polypropylene, granulate, at plant/RER U

Represents the oriented polypropylene sheet onto which the aluminum is deposited.

PET outer layer

Polyethylene terephthalate, granulate, amorphous, at plant/RER U

Represents average data for the production of virgin PET from ethylene glycol and PTA.

LLDPE inner layer

Polyethylene, LLDPE, granulate, at plant/RER U

Represents aggregated data for the production of virgin LLDPE.

12.6.2. Processing

Metallizing a polymer sheet

Section bar extrusion, aluminium/RER U

This process was used to represent the process for producing aluminum wire that is used in the metallization process. The wire is unrolled into the evaporation boats where it is heated, vaporized, and deposited upward onto the polymer sheet. The amount of this process required for the metallization of a polymer takes into account the overspray inefficiency as well.

Extrusion, plastic film/RER U

This represents the process of extruding the polypropylene sheet prior to being metallized.

Electricity, high voltage, production RER, at grid/RER U

This process represents the average electricity consumption associated with the steps of metallizing a polymer sheet. This electricity takes into consideration the material processed, stand-by energy, pump-down energy, metallizing energy, defrost energy, and inefficiencies associated with heat that is not directly converting aluminum to vapor.

Evaporation boats

Boron Nitride – this 'material' was not found within any databases in SimaPro. Therefore, a rudimentary process was created to represent the emissions of the material. As per CES EduPack 2014, it was determined that 6.82 kg of CO_2 and 0.379 kg of NOx are released during the primary production of boron nitride.

Titanium Diboride – this 'material' was not found within any databases in SimaPro. Therefore, a process was created that only represents some emissions of the material. As per CES EduPack 2014, it was determined that 4.83 kg of CO_2 and 0.027 kg of NOx are released during the primary production of titanium diboride.

PET film extrusion

Extrusion, plastic film/RER U

Represents the film conversion process and is noted that for one kg of input material results in 0.976 kg of extruded film.

LLDPE film extrusion

Extrusion, plastic film/RER U

Represents the film conversion process and is noted that for one kg of input material results in 0.976 kg of extruded film.

12.6.3. End of Life

Landfill Scenario - this represents the ratio of materials within the MOPP laminate that could be destined for the landfill. This landfill scenario was then specified at 80%, which associates 80% of each material to the landfill and specifies the impacts based on the quantity of each material.

Disposal, aluminium, 0% water, to sanitary landfill/CH U

Vaporized aluminum mass is 0.135 g, or 0.219%

Disposal, polypropylene, 15.9% water, to sanitary landfill/CH U

Polypropylene mass is 16.388 g, or 26.62%

Disposal, polyethylene terephthalate, 0.2% water, to sanitary landfill/CH U

PET mass is 16.475 g, or 26.77%

Disposal, polyethylene, 0.4% water, to sanitary landfill/CH U

LLDPE mass is 28.555 g, or 46.39%

Incineration Scenario - this represents the ratio of materials within the MOPP laminate that could be destined for incineration. This incineration scenario was then specified at 20%, which associates 20% of each material to incineration and specifies the impacts based on the quantity of each material.

Disposal, aluminium, 0% water, to municipal incineration/CH U

Vaporized aluminum mass is 0.135 g, or 0.219%

Disposal, polypropylene, 15.9% water, to municipal incineration/CH U

Polypropylene mass is 16.388 g, or 26.62%

Disposal, polyethylene terephthalate, 0.2% water, to municipal incineration/CH U

PET mass is 16.475 g, or 26.77%

Disposal, polyethylene, 0.4% water, to municipal incineration/CH U

LLDPE mass is 28.555 g, or 46.39%

Evaporation boat landfill scenario

Disposal, inert material, 0% water, to sanitary landfill/CH U

This is the process chosen to represent the end of life for the evaporation boats. 100% of the evaporation boats are assumed to be processed via landfill.

Aluminum recycling

Aluminium, secondary, from old scrap, at plant/RER U

The process of recycling aluminum and the impacts associated with it are represented by this process. This study did not credit the replacement of virgin aluminum, through this recycling process, back to the metallized polymer alternatives. To take this into consideration, primary aluminum would have been recorded as an output to technosphere as an avoided product.

12.7. PET/MPET/LLDPE Model Notes

The raw materials, processing, and end of life descriptions for the MPET laminate are recorded in the following section. In italics are the actual processes from the SimaPro inventory that were used to best represent each phase. All processes were taken from the ecoinvent database for this particular model.

12.7.1. Raw Materials

Metallized PET

Aluminium, primary, at plant/RER S

Accounts for the aluminum deposited onto the PET sheet as well as the 50% overspray associated with the metallization process

Polyethylene terephthalate, granulate, amorphous, at plant/RER U

Represents the polyethylene terephthalate sheet onto which the aluminum is deposited.

PET outer layer

Polyethylene terephthalate, granulate, amorphous, at plant/RER U

Represents average data for the production of virgin PET from ethylene glycol and PTA.

LLDPE inner layer

Polyethylene, LLDPE, granulate, at plant/RER U

Represents aggregated data for the production of virgin LLDPE.

12.7.2. Processing

Metallizing a polymer sheet

Section bar extrusion, aluminium/RER U

This process was used to represent the process for producing aluminum wire that is used in the metallization process. The wire is unrolled into the evaporation boats where it is heated, vaporized, and deposited upward onto the polymer sheet. The amount of this process required for the metallization of a polymer takes into account the overspray inefficiency as well.

Extrusion, plastic film/RER U

This represents the process of extruding the polyethylene terephthalate sheet prior to being metallized.

Electricity, high voltage, production RER, at grid/RER U

This process represents the average electricity consumption associated with the steps of metallizing a polymer sheet. This electricity takes into consideration the material processed, stand-by energy, pump-down energy, metallizing energy, defrost energy, and inefficiencies associated with heat that is not directly converting aluminum to vapor.

Evaporation boats

Boron Nitride – this 'material' was not found within any databases in SimaPro. Therefore, a rudimentary process was created to represent the emissions of the material. As per CES EduPack 2014, it was determined that 6.82 kg of CO_2 and 0.379 kg of NOx are released during the primary production of boron nitride.

Titanium Diboride – this 'material' was not found within any databases in SimaPro. Therefore, a process was created that only represents some emissions of the material. As per CES EduPack 2014, it was determined that 4.83 kg of CO_2 and 0.027 kg of NOx are released during the primary production of titanium diboride.

PET film extrusion

Extrusion, plastic film/RER U

Represents the film conversion process and is noted that for one kg of input material results in 0.976 kg of extruded film.

LLDPE film extrusion

Extrusion, plastic film/RER U

Represents the film conversion process and is noted that for one kg of input material results in 0.976 kg of extruded film.

12.7.3. End of Life

Landfill Scenario - this represents the ratio of materials within the MPET laminate that could be destined for the landfill. This landfill scenario was then specified at 80%, which associates 80% of each material to the landfill and specifies the impacts based on the quantity of each material.

Disposal, aluminium, 0% water, to sanitary landfill/CH U

Vaporized aluminum mass is 0.135 g, or 0.219%

Disposal, polyethylene terephthalate, 0.2% water, to sanitary landfill/CH U

PET mass is 16.390 g, or 26.63% (sheet onto which alum. is deposited)

Disposal, polyethylene terephthalate, 0.2% water, to sanitary landfill/CH U

PET mass is 16.475 g, or 26.77%

Disposal, polyethylene, 0.4% water, to sanitary landfill/CH U

LLDPE mass is 28.555 g, or 46.39%

Incineration Scenario - this represents the ratio of materials within the MPET laminate that could be destined for incineration. This incineration scenario was then specified at 20%, which associates 20% of each material to incineration and specifies the impacts based on the quantity of each material.

Disposal, aluminium, 0% water, to municipal incineration/CH U

Vaporized aluminum mass is 0.135 g, or 0.219%

Disposal, polyethylene terephthalate, 0.2% water, to municipal incineration/CH U

PET mass is 16.390 g, or 26.63% (sheet onto which alum. is deposited)

Disposal, polyethylene terephthalate, 0.2% water, to municipal incineration/CH U

PET mass is 16.475 g, or 26.77%

Disposal, polyethylene, 0.4% water, to municipal incineration/CH U

LLDPE mass is 28.555 g, or 46.39%

Evaporation boat landfill scenario

Disposal, inert material, 0% water, to sanitary landfill/CH U

This is the process chosen to represent the end of life for the evaporation boats. 100% of the evaporation boats are assumed to be processed via landfill.

Aluminum recycling

Aluminium, secondary, from old scrap, at plant/RER U

The process of recycling aluminum and the impacts associated with it are represented by this process. This study did not credit the replacement of virgin aluminum, through this recycling process, back to the metallized polymer alternatives. To take this into consideration, primary aluminum would have been recorded as an output to the technosphere as an avoided product.

12.8. Equations

12.8.1. Metallization Energy Calculation

The total energy calculated for the metallization process is per square meter of film.

Total Energy = (Stand-by Energy + Pump-down Energy + Metallizing Energy + Defrost Energy) ÷ (Material Processed)

Stand-by Energy = (Stand-by Time * Stand-by Power)

Pump-down Energy = (Pump-down Time * Pump-down Power)

Metallizing Energy = (Metallizing Time * Metallizing Power)

Defrost Energy = (Defrost Time * Defrost Power)

Total Energy = ((0.25*140.73) + (0.15*208.93) + (1.2*587.11) + (0.08*198.74)) ÷ (156240))

= 0.00504 [kWh/m^2] * 3.6 [MJ/kWh] = 0.01815 [MJ/m^2]

12.8.2. Evaporation Boat Calculation

The degradation of the evaporation boats is per square meter of film.

Consumed Average = (Mass of One Boat * Number of Boats * (Metallizing Time ÷ Boat Life Span)) ÷ (Material Processed)

Consumed Average = (0.132 * 33 * (1.2 ÷ 15)) ÷ (156240)

= 2.23E-06 [kg/m^2]

12.8.3. Waste to Energy Calculations

The potential electrical energy and carbon offsets produced from waste to energy incineration is per square meter of film.

Potential Electrical Energy Production = (Heating Value of Polymers * WTE Efficiency * Mass of Polymers) * (Incineration Ratio)

Aluminum Foil Laminate Electrical Energy = ((Heating Value_PET * WTE Efficiency * Mass_PET) + (Heating Value_LLDPE * WTE Efficiency * Mass_LLDPE)) * (Incineration Ratio)

MOPP Laminate Electrical Energy = ((Heating Value_PET * WTE Efficiency * Mass_PET) + (Heating Value_LLDPE * WTE Efficiency * Mass_LLDPE) + (Heating Value_OPP * WTE Efficiency * Mass_OPP)) * (Incineration Ratio)

MPET Laminate Electrical Energy = ((Heating Value_PET * WTE Efficiency * Mass_PET) + (Heating Value_LLDPE * WTE Efficiency * Mass_LLDPE) + (Heating Value_PET * WTE Efficiency * Mass_PET)) * (Incineration Ratio)

For the 80% landfill 20% incineration scenario:

Aluminum Foil Laminate Electrical Energy = ((25 * 0.178 * 16.475/1000) + (46 * 0.178 * 28.555/1000)) * (0.20)

$$= 0.061 \text{ [MJ/m}^2\text{]}$$

MOPP Laminate Electrical Energy = ((25 * 0.178 * 16.475/1000) + (46 * 0.178 * 28.555/1000) + (46 * 0.178 * 16.387/1000)) * (0.20)

$$= 0.088 \text{ [MJ/m}^2\text{]}$$

MPET Laminate Electrical Energy = ((25 * 0.178 * 16.475/1000) + (46 * 0.178 * 28.555/1000) + (25 * 0.178 * 16.390/1000)) * (0.20)

$$= 0.076 \text{ [MJ/m}^2\text{]}$$

For the 50% landfill 50% incineration scenario:

Aluminum Foil Laminate Electrical Energy = ((25 * 0.178 * 16.475/1000) + (46 * 0.178 * 28.555/1000)) * (0.50)

$$= 0.154 \text{ [MJ/m}^2\text{]}$$

MOPP Laminate Electrical Energy = ((25 * 0.178 * 16.475/1000) + (46 * 0.178 * 28.555/1000) + (46 * 0.178 * 16.387/1000)) * (0.50)

$$= 0.221 \text{ [MJ/m}^2\text{]}$$

MPET Laminate Electrical Energy = ((25 * 0.178 * 16.475/1000) + (46 * 0.178 * 28.555/1000) + (25 * 0.178 * 16.390/1000)) * (0.50)

$$= 0.190 \text{ [MJ/m}^2\text{]}$$

Carbon Offset = (Potential Electrical Energy Production * US Electrical Grid Carbon Footprint per MJ)

For the 80% landfill 20% incineration scenario:

Aluminum Foil Laminate = (0.061 * 0.191)

$$= -0.012 \text{ [kg } CO_2 \text{ eq.]}$$

MOPP Laminate = (0.088 * 0.191)

$$= -0.017 \text{ [kg } CO_2 \text{ eq.]}$$

MPET Laminate = (0.076 * 0.191)

$$= -0.015 \text{ [kg } CO_2 \text{ eq.]}$$

12.9. Metallized Polymer Specification Sheets

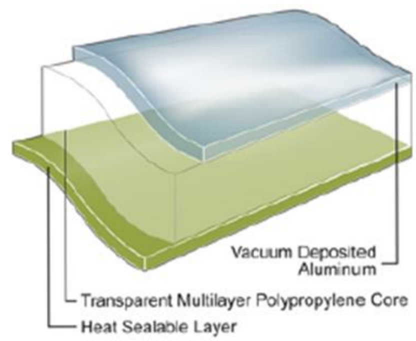
12.9.1. MOPP

Jindal Films

Metallyte™ 70 MET-HB2 PRELIMINARY
Oriented Polypropylene Film

Product Description

Metallyte 70 MET-HB2 is a vacuum-metallized, high barrier OPP film with a proprietary sealant layer. This film offers excellent moisture and oxygen barriers, hot tack, seal integrity, and lap seal range when used with a coextruded outer web. It provides excellent light barrier and a brilliant foil appearance. MET-HB2 is designed specifically for adhesive and craze-resistant extrusion laminations.



Key Features

- Good oxygen barrier
- Outstanding moisture and light barriers
- Low MST, broad seal range, strong seals
- High adhesion of aluminum to film
- Excellent hot tack

General	Metallyte™ 70 MET-HB2		
Availability[1]	• South America	• North America	• Latin America
Features	• In Lamination Lap Sealable	• Moisture Barrier	• Oxygen Barrier
	• Light Barrier		
Applications	• Biscuits/Cookie/Crackers	• Bakery	• Crisps and Snacks
Uses	• Pre-made Bags - Flexible Packaging	• HFFS Flexible Packaging	• VFFS Flexible Packaging
Appearance	• Metalized - Clear		
Processing Method	• Inner Web Adhesive Lamination	• Solvent Flexographic Printing	• Solvent Rotogravure Printing
	• Surface Print Unsupported	• Water-based Flexographic Printing	• Inner Web Extrusion Lamination
Revision Date	• October 10, 2013		

Properties	Metallyte™ 70 MET-HB2	Unit	Test Based On
Yield	44000	in^2/lb	Internal Method
Unit Weight	9.8	lb/ream	Internal Method
Film Thickness	0.70	mil	Internal Method
Optical Density	2.8		Internal Method
Tensile Strength at Break 20 in/min pull rate, 2.0 in jaw separation			
MD	18000	psi	Internal Method
TD	35000	psi	Internal Method
Dimensional Stability 275°F, 7 min			
MD	-4.5	%	Internal Method
TD	-6.0	%	Internal Method
Crimp Seal Strength 205°F, 20 psi, 0.75 sec	340	g/in	Internal Method
Crimp Seal MST (Minimum Seal Temperature)	192	°F	Internal Method
Water Vapor Transmission Rate 100°F, 90% RH	0.0040	$g/100\ in^2/24\ hr$	Internal Method
Oxygen Transmission Rate[2] 73°F, 0% RH	0.55	$cm^3/100\ in^2/24\ hr$	Internal Method

12.9.2. MPET

'TORAY'

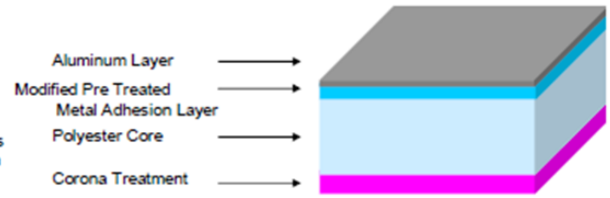
Innovation by Chemistry

Penfibre Sdn Bhd – Film Division

BR-PET 1012

Aluminum Metallized
Polyester Film

One side vacuum deposited Aluminum on Toray's modified pre treated surface, one side corona treatment. BR incorporates Toray's newest technology in providing high metal adhesion and stable barrier film. Designed for wide range of applications dry~wet.



KEY FEATURES

- High metal adhesion even under wet condition
- Guaranteed stable barrier
- Less pinhole, Non-craze metal surface
- Heat durability

APPLICATIONS

- Confectionery
- Liquid potion, Hot filling
- Personal care refilled
- Lid stock

TYPICAL STRUCTURES

- OPP/ink/ BR1012 / Sealant
- PET/ink/ BR1012 / Sealant
- ONY/ink/ BR1012 / Sealant
- PET/ink/ BR1012 / ONY / Sealant
- PET/ink/ ONY / BR1012 / Sealant

SIMILAR PRODUCTS

- (Under development)

TECHNICAL DATA

PROPERTIES		METHOD	UNITS	Typical Values
Thickness			micron	12
Nominal Yield			m^2/kg	59.5
Tensile Strength @ Break	MD TD	ASTM D882 JIS C2318	MPa	250 230
Young's Modulus	MD TD	ASTM D882 JIS C2318	MPa	4800 4700
Elongation @ Break	MD TD	ASTM D882 JIS C2318	%	110 125
Dimensional Stability (150°C for 30 minutes)	MD TD	ASTM D1204 JIS C2151	%	1.3 0.1
COF (Metal / Film)	Static Dynamic	ASTM D1894 JIS K7125	-	0.6 0.5
Wetting Tension	Metallized Corona	ASTM D2578 JIS K6768	Dyne/cm	> 52 > 52
Optical Density		Macbeth	-	2.2
O2TR @20°C, 0% RH		ASTM D3985 JIS K7126B	$cc/m^2/day$	0.6
MVTR @40°C, 90% RH		ASTM F1249 JIS K7129B	$g/m^2/day$	0.6
Metal adhesion	DRY WET	Toray Method	g/15mm (g/inch)	> 300 (500) > 300 (500)

DISCLAIMER

Toray has used its discretion, best judgment, and efforts in collecting and preparing the information provided herein, but such information is provided without any warranty of any kind, either expressed or implied, including, but not limited to, the warranties of completeness, accuracy, fitness for a particular purpose, or non-infringement. Changes can be periodically added to the information.

Penfibre Sdn. Bhd

Lot 128-130, Prai Free Industrial Zone 1, 13600 Prai, Penang, MALAYSIA
Tel : +60-4-3975588 Fax : +60-4-3977913